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J. Gruhl

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by

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ABSTRACT

This study is a review of projected emissions and energy efficiencies of coal-fired open cycle MHD power plants. Ideally one would like to develop empirically-based probabilistic models of MHD performance. However, with the lack of empirical information about full-sized facilities this survey concentrates on modeling analytically developed data. Also presented are discussions of unresolved MHD issues of importance, comprehensive lists of recent and ongoing research, and a bibliography of material related to emissions and efficiencies of coal-fired open cycle MHD power plants.

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1. Introduction

Recent reports (Pomeroy, et al., 1978) show open cycle (or binary) coal-fired magnetohydrodynamics, OCMHD, playing an extremely important role in our nation's energy future. Under certain assumed scenarios, such as no breeder reactors, open cycle MHD is overwhelmingly preferred once it is available (about the year 2003). That same study shows the large size (1932 MW) to be somewhat of a disadvantage that makes earlier penetration, if available, unlikely. Once available, however, the share of the market for OCMHD could be as large as 90% (Pomeroy, et al., 1978). Most forecasts show MHD dominating future coal-fired power plant markets, especially in scenarios where coal prices escalate rapidly.

Clearly this is an important advanced energy technology, yet there is currently not enough performance data to precisely assess the emissions or efficiency capabilities of OCMHD power plants. Appendix A displays the large uncertainties that exist concerning this information. The theoretically very high performance potential, meeting emissions standards with 50 to 60% conversion efficiency, and absence of moving parts and heat exchanges in the MHD cycle, have been the principal justifications for continued research and development. With the absence of full-sized facilities, this study concentrates on analytically derived data, ongoing research efforts, and problems and potential solutions for meeting the theoretical performance potential.

MHD is envisioned as a topping cycle to be operated in series with a steam cycle, see Figure 1-1. Coal is first processed then sent into a combustor where it is burned at very high temperatures, 2756 K to 3033 K (4500^{o}F to 5000^{o}F) and at high pressure, 7 to 15 atm. The gaseous

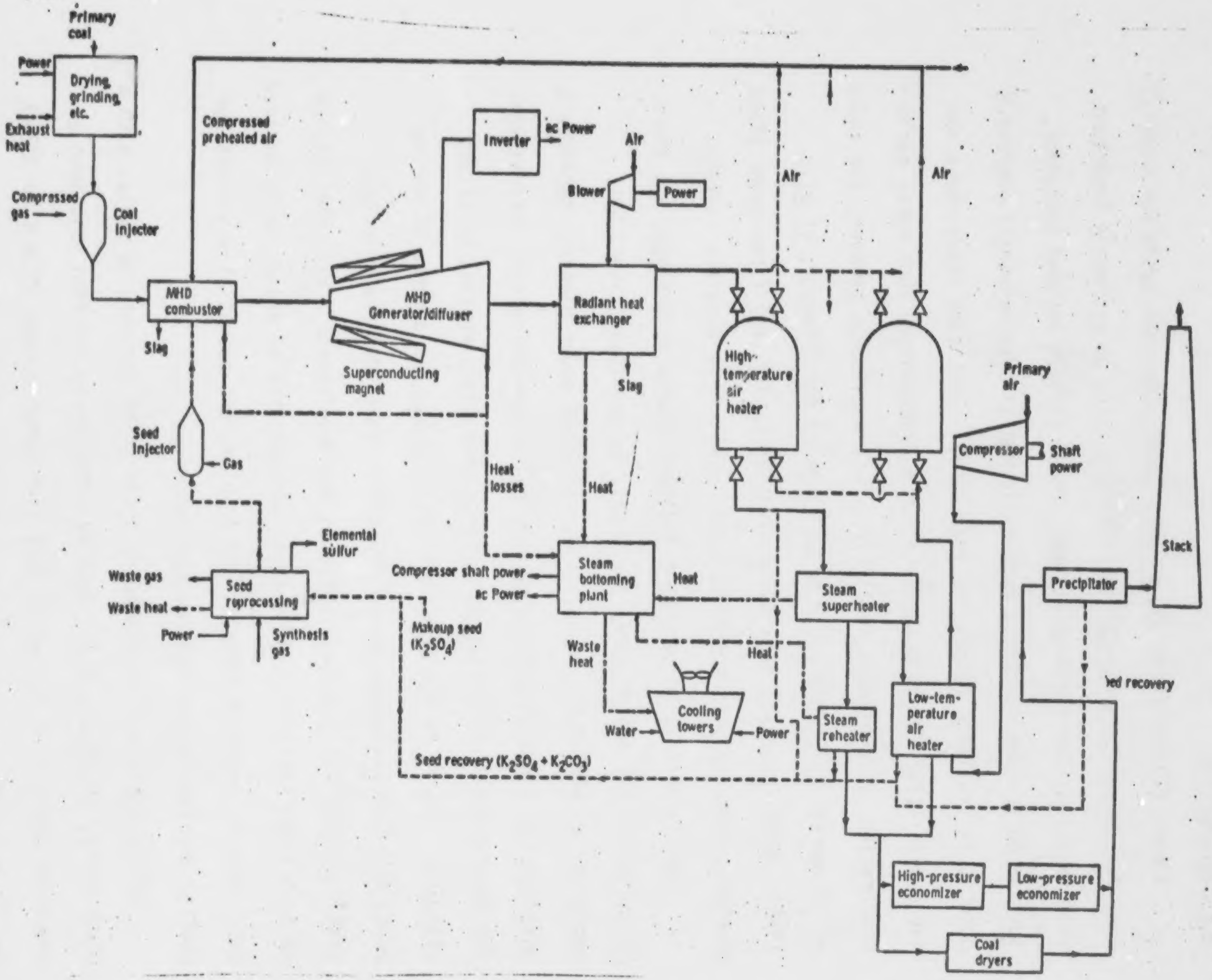

Primary coal
Power
Drying, grinding, etc.
Exhaust heat
Compressed gas
Coal injector
MHD combustor
Slag
Compressed preheated air
Inverter
ac Power
MHD Generator/diffuser
Superconducting magnet
Air
Blower
Power
Radiant heat exchanger
Slag
Air
Air
High-temperature air heater
Primary air
Compressor
Shaft power
Seed injector
Gas
Heat losses
Heat
Elemental sulfur
Waste gas
Waste heat
Power
Seed reprocessing
Synthesis gas
Makeup seed (K_2SO_4)
Compressor shaft power
ac Power
Steam bottoming plant
Heat
Steam superheater
Precipitator
Stack
Waste heat
Heat
ed recovery
Water
Cooling towers
Power
Steam reheater
Low-temperature air heater
Seed recovery ($K_2SO_4 + K_2CO_3$)
High-pressure economizer
Low-pressure economizer
Coal dryers

Figure 1-1 Basic Schematic of Open Cycle MHD (NASA,1977)

combustion products are made electrically conductive, about 10 to 12 mhos/m, by injection of a small fraction, about 1%, of seed material such as potassium carbonate. The conductive gas is then expanded at high velocity, about 1000 m/s, through a high magnetic field, about 5 to 8 Tesla, thus producing direct current at electrodes perpendicular to the flow field and magnetic field. The still hot gases, about 2256 K (3600°F), are then sent to a bottoming steam turbine. Before or after this turbine the gases usually will preheat the coal and/or air. In an open-cycle system the steam turbine exhaust usually goes to a water heater and then eventually up the stack. Some of the possible design variations that have been studied are outlined in Chapter 3.

Even considering nearly identical conditions, about 1617 K (2450°F) direct air preheat and a 24.1 MN/m^2/811K/811K (3500° psi/1000°F/1000°F) supercritical single reheat steam bottoming cycle, performance estimates are widely scattered, (see Table 1-1 and several others in this report) sometimes almost a factor of two variation on certain estimates ($642 versus $1102 investment cost per kWe). This large uncertainty in projected performance is the first major issue discussed in each of the following chapters.

The second issue elaborated is that of barriers that must be hurdled before commercialization of OCMHD. These technological problems are indirectly related to the issues of this paper. Thus they are only roughly summarized in Table 1-2, are listed in order of severity in Chapter 5, and are briefly mentioned in the sections of this report where they bear upon aspects of performance.

TABLE 1-1

AVAILABILITY AND COST COMPARISONS OF PROJECTED FULL-SIZE OPEN CYCLE COAL MHD DESIGNS

Capital Cost	
(Pomeroy, et al., 1978)	$805/kWe
(NASA, 1977)	$1103/kWe (Westinghouse)
(NASA, 1977)	$642/kWe (GE Co.)
(Seikel, Harris, 1976)	$718/kWe
(General Electric, 1975)	$910-$1440/kWe
(Pepper, Yu, 1975)	$340-$440/kWe
(Rosa, et al., 1970)	$35-$55/kWe (peaking)
(Hals, Jackson, 1969)	$90-$120/kWe
Cost of Electricity	
(Levi, 1978)	32 mills/kWh
(Pomeroy, et al., 1978)	34-43 mills/kWh (baseload)
(Pomeroy, et al., 1978)	130 mills/kWh (peaking)
(NASA, 1977)	27.1-43.9 mills/kWh
(Seikel, Harris, 1976)	42-49 mills/kWh (GE Co.)
(Seikel, Harris, 1976)	32-50 mills/kWh (WE Co.)
(Seikel, Harris, 1976)	31.8 mills/kWh (GE Co.)
(General Electric, 1975)	41.5-55.5 mills/kWh
(NASA, 1975)	41-48 mills/kWh (GE Co.)
(NASA, 1975)	27-35 mills/kWh (Westinghouse)
(NASA, 1975)	34-42 mills/kWh (low Btu, Westinghouse)
(Hals, Jackson, 1969)	3.34-4.26 mills/kWh
Construction Time	
(Pomeroy, et al., 1978)	5-6.5 years
(Seikel, Harris, 1976)	6.5 years
Date of Commercialization	
(Pomeroy, et al., 1978)	2003
(Penny, Bourgeois, Cain, 1977)	2000
(Seikel, Harris, 1976)	1996-1999
(Pepper, Yu, 1975)	1988

TABLE 1-2

SUMMARY OF MHD PROBLEM AREAS

Problems	Potential Solutions
Particulate Removal	
- submicron sizes	. facility testing
- high quality plasma with low ash	
Seed Recovery	
- efficiencies of recovery from solids	. seed collection . combustion modeling
- suitability for reuse	
- economic problems and energy costs	. thermal regeneration
- water contamination	
- ash composition peculiarities	
- atmospheric releases	
Nitrogen Oxide Control	
- may not meet standards	. minimize during combustion . reduce oxygen in high-temperature areas and inject air in low-temperature regions . post-combustion control . two-stage combustion . use different pressures . use different air/fuel ratios
Sulfur Oxide	
- potassium sulfate emissions	. facility testing
Properties of Coal	
- some fundamentals are important but not known or are widely varying	. kinetic conditions testing . devolatilization kinetics studies
- conductivity, ignition, devolatilization, combustion, gasification, slag vaporization, slag agglomeration	. ash vaporization studies
Moisture	
- in low-grade coals	. coal drying

TABLE 1-2 (continued)

SUMMARY OF MHD PROBLEM AREAS

Durable Materials, especially insulators, electrodes and heat exchangers	
- extremely high temperatures	. develop high grade materials
- corrosive exhaust gases	. develop predictive techniques for optimizing conditions and materials
- short life of nozzles, valves, boiler tubes and duct materials	. study high temperature and corrosion effects
- ash and seed corrosion of ceramic and metal parts	. study of thermal cycling and long duty cycle effects
Generator, Duct and Diffuser Life	
- effects of combustion products and slag on walls	. studies of properties of combustion products
- multiplicity of load circuits	. long duration tests
- axial breakdown limitation	. disk generators
Other Component Problems	
- demonstrate air preheaters	. facility testing
- slag coating of heat exchangers	
- high temperature heat exchangers	
- superconducting magnetic system cost, size, and temperature problems	
Combustors	
- 5000°F	. facility testing
- reasonably free of slag vapor 10-20% original ash	. more direct measurements and analytic modeling
- sufficient rate and uniform coal feed	
- good mixing with low pressure drop	
- high slag rejection and topping	
Large Facility Sizes	
- effects of components on each other	. development of smaller modules
- 2000 MW minimums	. testing of component interfaces
- reliability problems associated with large blocks of power	
- scale-up problems	
Turndown and Load Follow	. use several smaller modules

TABLE 1-2 (continued)

SUMMARY OF MHD PROBLEM AREAS

Demonstrate Enthalpy Extraction and Isentropic Efficiency	. short duration experiments
Absolute and Convective Instabilities	. large facility testing
Stable Electrical Loading	. large facility characteristics . analytic stability studies
Accurate Performance Estimates	
- efficiency and coal consumption	. optimum design specification
- capital cost and cost of electricity	. facility testing
- availability	. forecast of R&D funding levels
- adaptability to base load	
- likelihood and expected year of commercialization	

It is easy to be optimistic about the future of OCMHD, one just has to review the system's simplicity, the fallback positions, the time and funding available, and the progress to date (compared to the competing technologies, particularly the operating experimental facilities). However, it is also easy to be pessimistic, there are considerable technical problems associated with virtually every major power plant design component. Efficiencies and emissions will be significantly affected by the trade-offs and design changes resulting from future solutions for these technical problems, and this is a major reason for the significant uncertainties in the values reported in the following chapters.

2. MHD Programs in Progress

Research and development programs in MHD cycles have progressed erratically for more than a century (Levi, 1978), initially being linked to the work of Michael Faraday in 1831. Translation of the MHD concept into commercial application has been motivated recently by the need for efficient, clean methods of converting coal energy into electricity. Modern efforts began at Westinghouse starting in 1938 and were continued into the 1950's at Cornell University. Feasibility experiments were conducted in the 1960's first at Westinghouse, GE, and Avco and later at University of Tennessee and Stanford University.

Internationally, the Soviet Union has advanced, first in closed-cycle, later in open-cycle, facilities fueled by natural gas. The Japanese have been concentrating on use of heavy oils as fuels, primarily to reduce amounts of petroleum to be imported. In addition to the U.S. and U.S.S.R., Poland and India because of their significant fossil fuel resources have continued to conduct MHD research. The United Kingdom, France, and West Germany have essentially stopped their MHD programs although they have joined an international cooperative with the other principal research countries and some countries with relatively new interests: Australia, Austria, Belgium, Canada, Czechoslavakia, Hungary, Italy, Netherlands, Rumania, Sweden and Switzerland.

A summary of the more recent history of MHD development is shown in Figure 2-1. Excellent further historical discussions are contained in (Kantrowitz, 1977), (Way, 1971), and (Tager, Henry, 1976).

It would take a considerable effort to describe all the current and future plans for MHD in the U.S. Instead Table 2-1 lists the

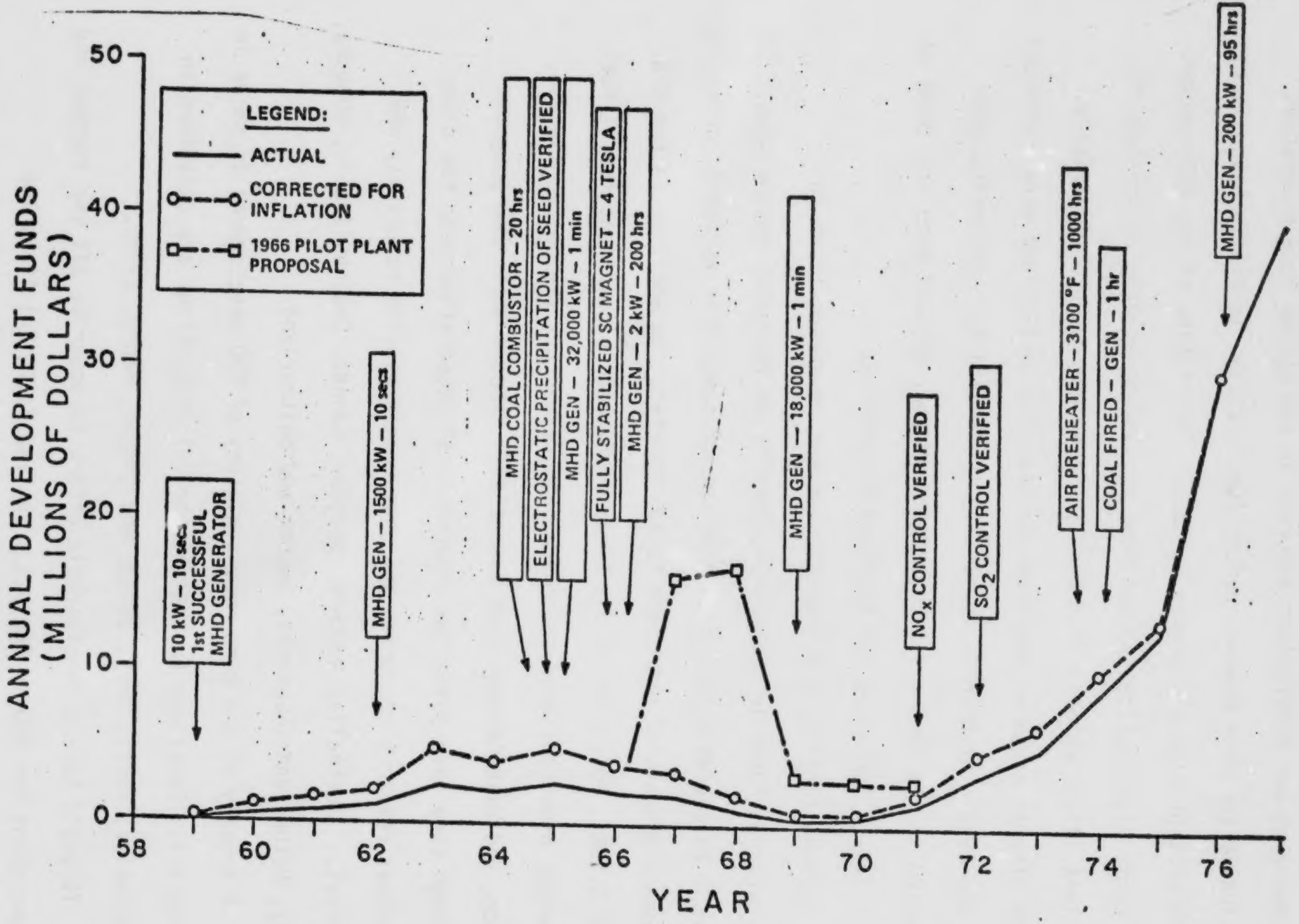


Figure 2-1 General Description of the Evolution of Recent MHD Developments (Kantrowitz,1977)

TABLE 2-1

RECENT AND ONGOING MHD RESEARCH

Argonne National Lab	- generator phenomena - combustion studies and modeling - project planning and definition - systems studies - magnets
Arnold Engineering Development Center	- component and materials experiments - high enthalpy extraction - magnet testing and building - test facility
Avco-Everett Research Lab	- component and materials experiments - seed recovery - generator design - economic and environmental assessments - auxiliary component development - peaking plants - pollution control by gas cleaning - NO_x control experiments
Battelle Pacific Northwest Lab	- electrode development
Bechtel	- design evaluation - labor and materials studies - cooling water evaluations
British Coal Utilization Research Association	- combustion modeling
Brookhaven National Labs	- comparative assessments
Burns and Roe	- design
California Institute of Technology	- performance studies
Central Electricity Generating Board, Great Britian	- slag buildup on heat exchangers
Eindhoven, Holland	- closed-cycle facility
Electrotechnical Lab of Japan	- oil-fired MHD -Mark V, VI

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

EPRI	- market penetration - R&D funding
Exxon Research & Engineering Co.	- evaluation of designs
Flinders University of South Australia	- comparative assessments
Fluidyne Corporation	- air preheaters - facility design and evaluation
Foster-Wheeler	- design evaluation - evaluation of auxiliaries
Gilbert Associates Inc.	- design studies
General Electric Co.	- MHD market penetration - design and evaluation of facilities - preheater development
Hercules Powder Corp	- support studies
Hittman Associates Inc.	- comparative assessments
Institute of Gas Technology	- comparative assessments
International Atomic Energy Agency, Vienna	- MHD commercialization potential
Krzhizhnavosky Power Institute	- prototype MHD plant
Laboratory of Direct Conversion of Italy	- closed-cycle facility
Arthur D. Little, Inc.	- comparative assessment
Lockheed-Huntsville Research & Engineering	- environmental assessments
Max Planck Institute of Plasma Physics of Germany	- combustion modeling - closed-cycle facility
Maxwell Labs	- support studies

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

MEPPSCO	- generator design - magnet design
Mississippi State University	- corrosion studies
M.I.T.	- magnet design - emission modeling and control - combustion modeling - modular design tool - generator performance - disc generator experiments - materials problems - seed recovery experiments
Montana Energy and MHD R&D Institute	- research facilities
Montana State University	- air preheaters
National Bureau of Standards	- materials problems - electrodes - slag characteristics
National Science Foundation	- basic research funding - comparative study funding
North Carolina State University	- electrode materials
Nuclear Energy Agency (OECD)	- international cooperation
Oak Ridge National Labs	- comparative assessment
Parsons	- design studies
Rand Corporation	- closed-cycle examination - overview studies
Reynolds Metals	- gaseous electrode development
Rockwell International	- design studies - space applications
Stanford Research Institute	- comparative assessments

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

Stanford University	- test facility - generator phenomena - magnet design and effects - NO_x modeling and control - cooling requirements
STD Research Corporation	- design and systems studies - coal drying - retrofit to older plants
Systems Research Labs	- support studies
Teknekron, Inc.	- comparative assessments
Tokyo Institute of Technology	- NO_x modeling
TRW Energy Systems	- evaluation of designs - prototype combustors
University of Illinois at Chicago	- combustion modeling
University of Mississippi	- performance studies
University of Montana	- support studies
University of Pittsburgh	- seed regeneration - slag effects - downstream components
University of Tennessee	- seed recovery - experimental facility
University of Tokyo	- systems studies
U.S. Bureau of Mines, Morgantown	- seed regeneration - seeded coal combustion properties
U.S. DOE	- R&D funding - experimental programs - commercial demonstration
U.S. DOE Pittsburgh Energy Research Center	- seeding and seed recovery and regeneration - environmental emissions - combustion experiments - coal drying

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

U.S. EPA	- environmental assessments
U.S. NASA	- comparative study funding - design and evaluation
U.S. Senate, Office of Technology Assessment	- overview of government role in MHD - comparison with other energy cycles
U.S.S.R.	- sponsoring MHD research and development
USSR Atomic Energy Institute	- systems studies
USSR Institute for High Tempertures	- MHD research - facilities
Westinghouse Research Labs	- design and evaluation of facilities - systems studies - experimental facility
Whittaker Corporation	- unconventional designs - systems studies
Wright-Patterson AFB	- systems studies

organizations involved and the general research and development areas to which they are contributing. In addition to EPRI sponsorship, a recent tally of government funding of MHD studies (Penny, Bourgeois, Cain, 1977) showed DOE with 81%, DOD 13%, and NSF 6%, of the $8.15 million being spent on 37 projects. Current facilities are listed in Table 2-2 and some of the future U.S. facilities are listed in Table 2-3. The approximate timing of these future facilities is shown in the ECAS study in Figure 2-2 and in an accelerated forecasted from DOE and EPRI in Figure 2-3. Two ideas about the logical process of the research and development necessary to support this facility timetable are shown in Figures 2-4 and 2-5.

Table 2-2 Main Parameters of Some Open Cycle MHD Genrators Presently in Use (Argyropolis, 1976, pp 64-66)

FACILITY	OPERATION TIME	THERMAL POWER MW	ELEC. POWER MW	MASS FLOW (Kg/s)	SPECIFIC ELEC. POWER (MJ/kg)	ENTHALPY EXTRACTION η_{ent}	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	ELEC. POWER DENSITY (MW/m^3)	T_0 (°K)	P_0 (atm)	M inlet	ELECTRODES	B (T)	SEED
USSR IED Kiev	3 h	8.35	0.015	2	0.0075	0.0016	natural gas	O_2/N_2=2/3	-	-	2850	-	0.7	Sic 6 pairs	1.5	KOH in alcohol
USSR (ENIN-II	10 min	140-160	0.2-1.5	12-14	0.014-0.1	0.0013-0.01	-	O_2	20x20 20x50 L-300	1-7.5	3200	10-12	2	brass 116 pairs	1.5	K_2CO_3 in water
USSR IHT (U-02)	200 h	5	0.075	1	0.075	0.015	-	O_2/N_2=1 T_{ox}=1100°C	20x6.4 40x6.4 L-300	1.32	2900	1.2	0.8	ZrO_2, Sic 52 pairs	1.7	Cs_2CO_3 in water
USSR IHT (U-25)	1000 h	300	20	50	0.4	0.066	-	O_2/N_2=2/3 T_{ox}=1200°C	38x77 38x138 L-500	12	2900	3.2	0.8	copper; ceramics	2	K_2CO_3 in water 65%
POLAND Tech.Univ. Poznan	long term	4	-	0.8	-	--	liquid hydrocarbon	O_2 or preheated air	3x10x50	-	3100	1	1	various materials	3.5	KOH in alcohol
POLAND IBJ	1 h	30	-	3	-	-		O_2	-	-	-	-	-	-	-	KOH in alcohol
JAPAN ETL (Mark-II) hot wall	10 min	10	0.251	2.5	0.10	0.025	gas, oil	O_2/N_2=1 T_{ox} = 1320°C	9x15 9x25 L-120	11.6	2780	2.8	>1	graphite 30 pairs	3.3	K_2SO_4 power 1% K in fuel
JAPAN ETL (Mark-II semi-hot wall	-	-	0.019	-	0.0076	0.0019	-	-	-	0.88	-	-	-	ZrB_2(80%)	-	-

Table 2-2 Main Parameters (cont.)

FACILITY	OPERATION TIME	THERMAL POWER	ELEC. POWER	MASS FLOW (Kg/s)	SPECIFIC ELEC. POWER (MJ/kg)	ENTHALPY EXTRACTION TION η_{ent}	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	ELEC. POWER DENSITY (MW/m^3)	T_0 (°K)	P_0 (atm)	M inlet	ELECTRODES	B (T)	SEED
JAPAN ETL (Mark III)	100 h	3.6	-	0.5	-	-	diesel oil	air + O_2	3x12x90	-	-	-	0.8	12 pairs	1.9	KOH
JAPAN ETL (Mark VI)	100 h	1	-	0.66	-	-	light oil	enriched air, T_{ox}=1400°C	3x12x90	-	-	-	1.9	—	-	ag KOH
JAPAN ETL (Mark V)	1 h	25	0.5	- 1.5-3.5			light oil	oxygen	F_1=140 cm^2 F_2=250 cm^2 L =192 cm				~1.	anode: stainless steel cathode: Cu-W 50 pairs	3.9	aq KOH
USA AVCO (Mark VIC)	25o ~~100~~ h	20	0.5	2.8	0.17	0.05	oil or kerosene, slag	O_2/N_2=2	F_1=400 cm^2 F_1=800 cm^2 L=200 cm	12.5	3200	8	2	Inonel	3.2	K_2CO_2 [STET]
USA AVCO Mark V	1 min	-	50													
USA WPAFB (KIVA-I)	1 min	6	0.2	0.6	0.5	0.05	toluene, JP4	O_2	2.6x10 7.2x11 L=85	80	3300	10	2	50 pairs	2.7	Cs_2CO_3
USA Stanford U. (M-2)	3 h	2-3	-	-	-	-	CH_3OH	N_2/O_2=1/2	3x10x61	-	2900	1.5	8	stainless steel 13 pairs	2.5	1% K
USA Stanford U. (M-8)	3 h	8	0.1	0.5	0.125	-	kerosene	O_2	3.9x10 6.3x10 L=70	20	3300	5	1.7	various materials 22 pairs	2.5	KOH in alcohol
USA AEDC (HPDE)	2o ~~15~~ sec.	320-460	45-65	50-65	-	.16	toluene, later with slag	N_2/O_2=1.25	26x51 102x128 L=920	-	3100	5.4	0.8	copper w/ granite caps 173 pairs	6	KOH in CH_3OH

Table 2-2 Main Parameters (cont.)

FACILITY	OPERATION TIME	THERMAL POWER	ELEC. POWER	MASS FLOW (Kg/s)	SPECIFIC ELEC. POWER (MJ/kg)	ENTHALPY EXTRACTION η_{ent}	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	ELEC. POWER DENSITY (MW/m^3)	T_0 (°K)	P_0 (atm)	M inlet	ELEC-TRODES	B (T)	SEED
USA AEDC LORHO	1 min	-	20													
USA Westing-house	100 h	4-5	.1	1.5	-	-	toluene, char, later with slag	air $T_{ox}\approx 900$°C	8x11x100	-	2600	4	0.9	various mat'ls. 50 pairs	3	K_2CO_3
USA (UTSI-I)	8 s	8.35	0.07	0.8	0.09	0.0084	kerosene & powerful additives	O_2	9.5x20.5x 120	2.8	3200	3-4.5	2	copper 60 pairs	2.2	KOH and KNO_2 in alcohol Cs_2CO_3
USA (UTSI-II)	8 s	8.35	0.04	0.8	0.04	0.0047	coal	O_2	5.8x15x90	-	3200	3-5	2	copper 40 pairs	2.2	K
USA (UTSI-III)	long term	8.35	0.09	0.8	-	-	coal	O_2	5.8x30x90	-	3000	4.5	1.4	copper	2.2	K
USA Reynolds Metals	long term	-	-	-	-	-	diesel fuel	N_2/O_2=1	2.6x5.1x26	-	2200	-	<1	-	2	K
USA Reynolds Metals	long term	-	-	4.4	-	-	diesel fuel	N_2/O_2=1	21x36x154	-	2200	-	<1	-	4.2	K
USA PERC	-	5.0														

Table 2-3 Main Parameters of Some Planned Open Cycle MHD Generators (Argyropolis, 1976, p. 67)

FACILITY	EXPECTED DATE OF OPERATION	THERMAL POWER	MHD ELEC. POWER	STEAM ELEC. POWER	MASS FLOW (Kg/s)	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	T_0 (°K)	P_0 (atm)	M inlet	B (T)	SEED
USA (CFFF)	1978	20	-	-	3.6	coal							
USA (CDIF) MEMRDI	1978	50	9	9	10	coal	air T_{ox}=2125-2250°C	-	-	8-10	.9	3.5	K_2CO_3
USA (ETF) MEMRDI	1981	250	70	70	46	coal	air T_{ox}=2125-2250°C	-	-	8-10	.9	3.5	K_2CO_3
USA (CDP)	1980's	1000	-	500	-	coal							

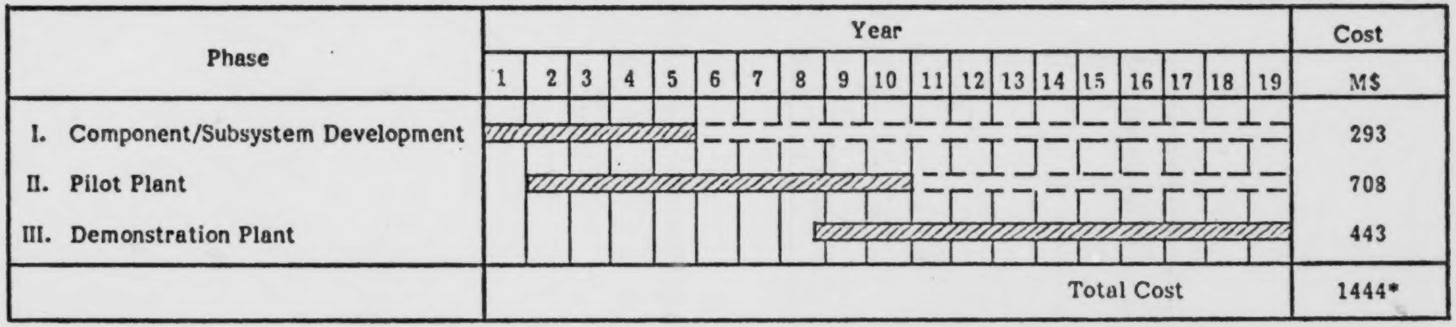


Figure 2-2 Schedule and Costs For Development Plan - Open Cycle MHD (General Electric, 1976)

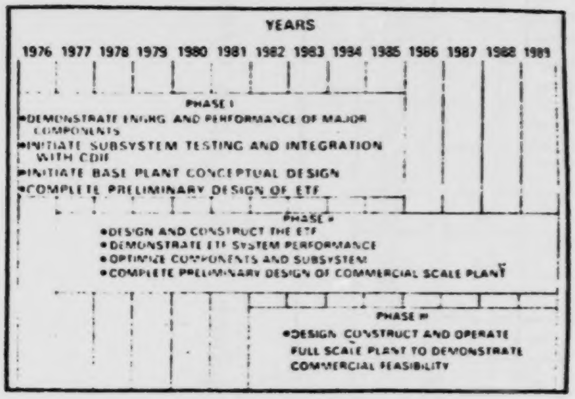


Figure 2-3 Major MHD Program Phases (Jackson,et al., 1976)

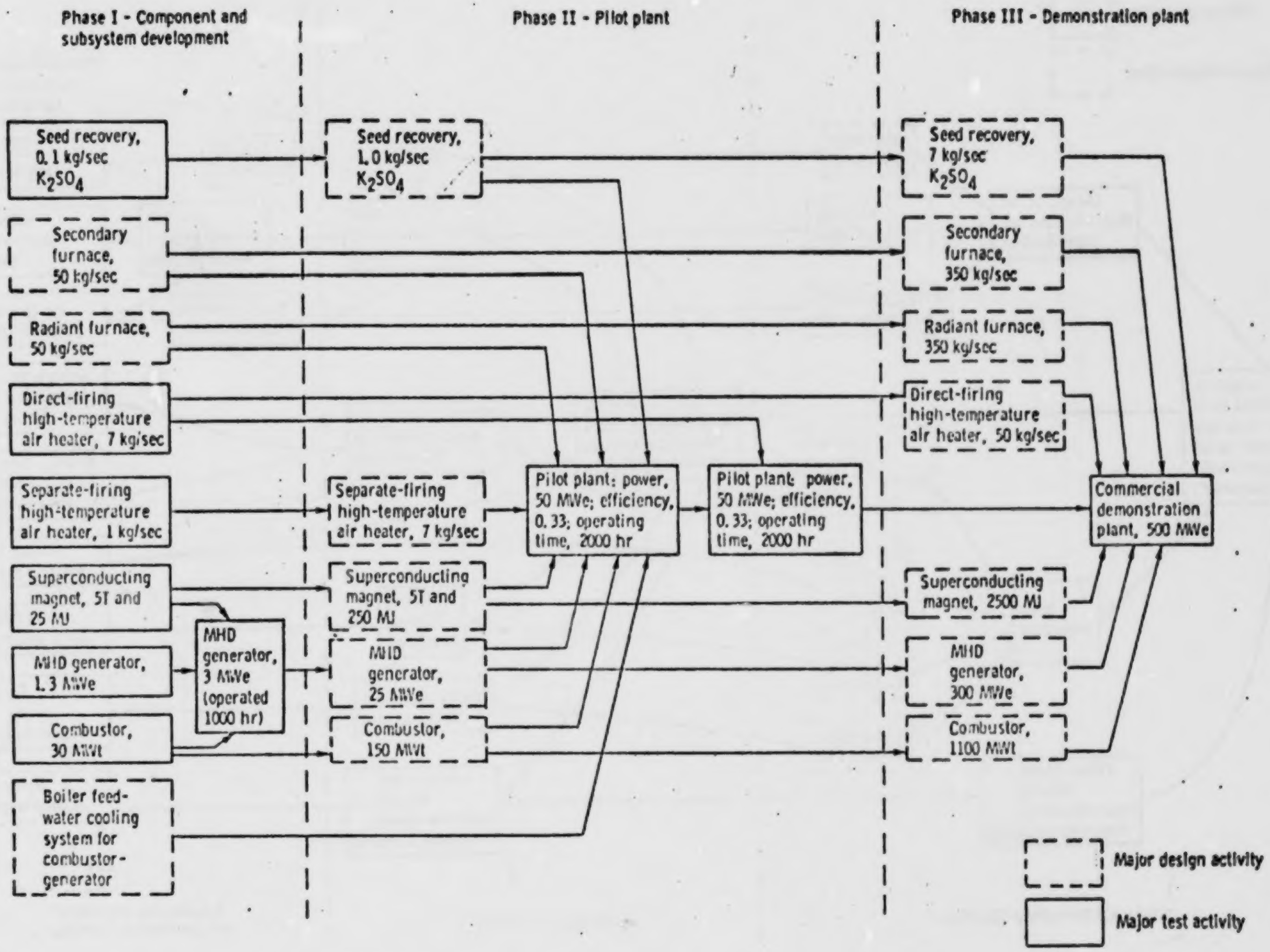

Phase I - Component and subsystem development
Phase II - Pilot plant
Phase III - Demonstration plant
Seed recovery, 0.1 kg/sec K_2SO_4
Secondary furnace, 50 kg/sec
Radiant furnace, 50 kg/sec
Direct-firing high-temperature air heater, 7 kg/sec
Separate-firing high-temperature air heater, 1 kg/sec
Superconducting magnet, 5T and 25 MJ
MHD generator, 1.3 MWe
Combustor, 30 MWt
Boiler feed-water cooling system for combustor-generator
MHD generator, 3 MWe (operated 1000 hr)
Seed recovery, 1.0 kg/sec K_2SO_4
Separate-firing high-temperature air heater, 7 kg/sec
Superconducting magnet, 5T and 250 MJ
MHD generator, 25 MWe
Combustor, 150 MWt
Pilot plant: power, 50 MWe; efficiency, 0.33; operating time, 2000 hr
Pilot plant: power, 50 MWe; efficiency, 0.33; operating time, 2000 hr
Seed recovery, 7 kg/sec K_2SO_4
Secondary furnace, 350 kg/sec
Radiant furnace, 350 kg/sec
Direct-firing high-temperature air heater, 50 kg/sec
Superconducting magnet, 2500 MJ
MHD generator, 300 MWe
Combustor, 1100 MWt
Commercial demonstration plant, 500 MWe
Major design activity
Major test activity

Figure 2-4 Avco Logic Flow Diagram for Coal/Open-Cycle MHD/Steam System Development Plan (NASA, 1977)

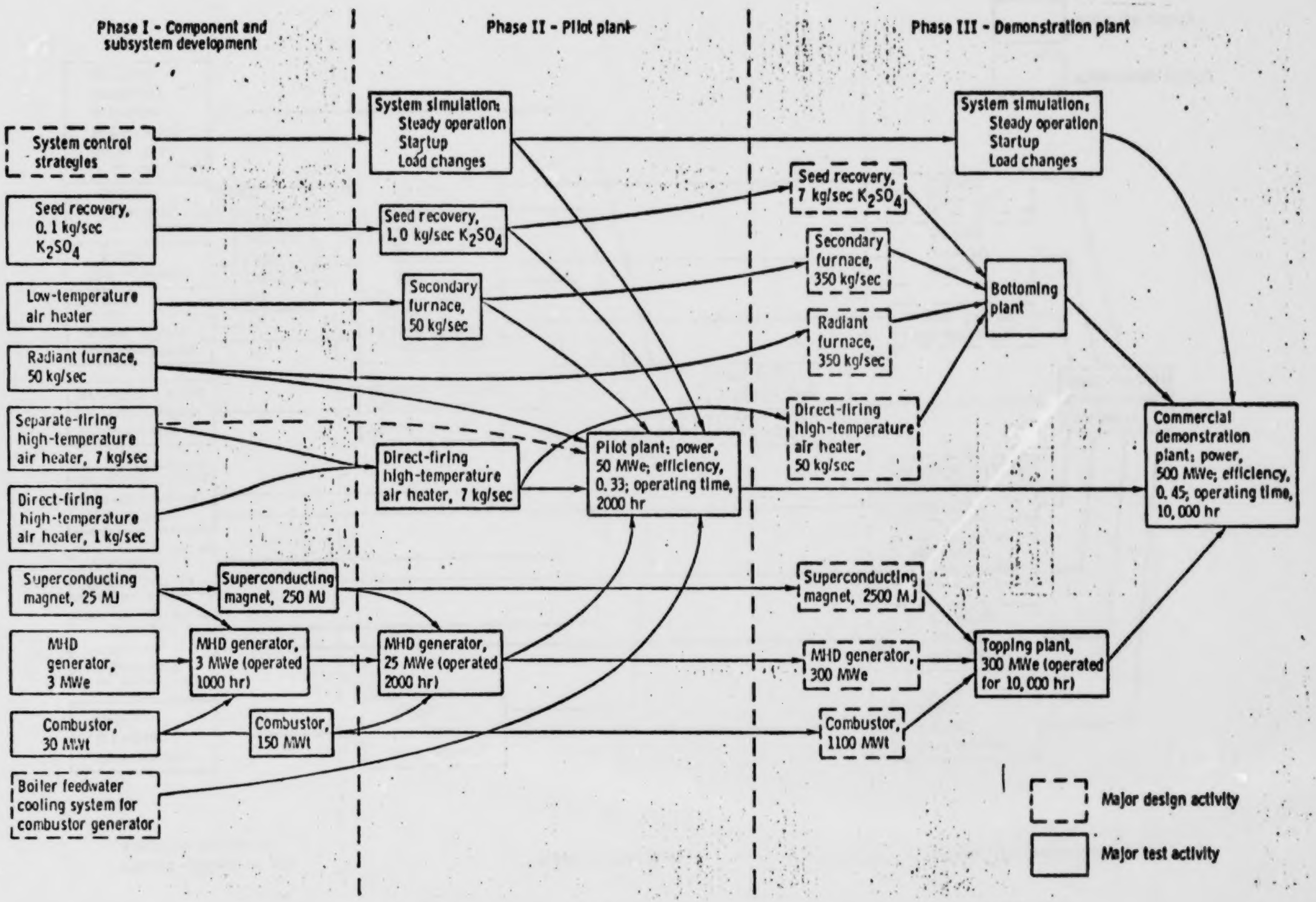

Phase I - Component and subsystem development
Phase II - Pilot plant
Phase III - Demonstration plant
System control strategies
Seed recovery, 0.1 kg/sec K_2SO_4
Low-temperature air heater
Radiant furnace, 50 kg/sec
Separate-firing high-temperature air heater, 7 kg/sec
Direct-firing high-temperature air heater, 1 kg/sec
Superconducting magnet, 25 MJ
MHD generator, 3 MWe
Combustor, 30 MWt
Boiler feedwater cooling system for combustor generator
Superconducting magnet, 250 MJ
MHD generator, 3 MWe (operated 1000 hr)
Combustor, 150 MWt
System simulation: Steady operation Startup Load changes
Seed recovery, 1.0 kg/sec K_2SO_4
Secondary furnace, 50 kg/sec
Direct-firing high-temperature air heater, 7 kg/sec
MHD generator, 25 MWe (operated 2000 hr)
Pilot plant: power, 50 MWe; efficiency, 0.33; operating time, 2000 hr
Seed recovery, 7 kg/sec K_2SO_4
Secondary furnace, 350 kg/sec
Radiant furnace, 350 kg/sec
Direct-firing high-temperature air heater, 50 kg/sec
Superconducting magnet, 2500 MJ
MHD generator, 300 MWe
Combustor, 1100 MWt
System simulation: Steady operation Startup Load changes
Bottoming plant
Topping plant, 300 MWe (operated for 10,000 hr)
Commercial demonstration plant: power, 500 MWe; efficiency, 0.45; operating time, 10,000 hr
Major design activity
Major test activity

Figure 2-5 General Electric's Revised Logic Flow Diagram for Coal/Open-Cycle MHD/Steam System Development Plan (NASA, 1977)

3. Plant Design Configurations

In addition to choices between open-cycle and closed-cycle there are a tremendous number of possible MHD design variations. In Phase I of the ECAS study the open-cycle variations included:

(1) coal, solvent refined coal, or coal gasifier products as fuels;

(2) air or oxygen-enriched air as oxidant;

(3) direct air preheat using MHD exhaust, or indirect (separate) preheating using coal volatiles or a coal gasifier product, or combinations of direct and indirect preheats; and

(4) steam bottoming cycles or gas-turbine bottoming cycles.

An excellent display of the MHD configuration options is shown in Figure 3-1 from (Jackson, et al., 1976). This diagram shows that for coal-fired OCMHD the principal distinguishing feature is the high-temperature preheat or regeneration procedure. The regeneration procedures could involve anything from using the MHD exhaust heat to produce a clean fuel for indirect air preheaters, to using direct air preheaters with the MHD exhaust heat utilized to generate heated, clean fuel for the MHD combustor. The simplicity of the MHD process and the relatively early stage of its development are the reasons for the tremendous variety of designs.

Receiving the most attention lately (due to low expected cost of electricity) is the OCMHD design suggested in Phase II of the ECAS study (General Electric, 1976), called NASA Case 1. This configuration uses direct air preheating at 1316 K to 1371 K (2400^oF to 2500^oF), direct coal-fired combustor, and a 24.1 MN/m^2/811 K/811 K (3500

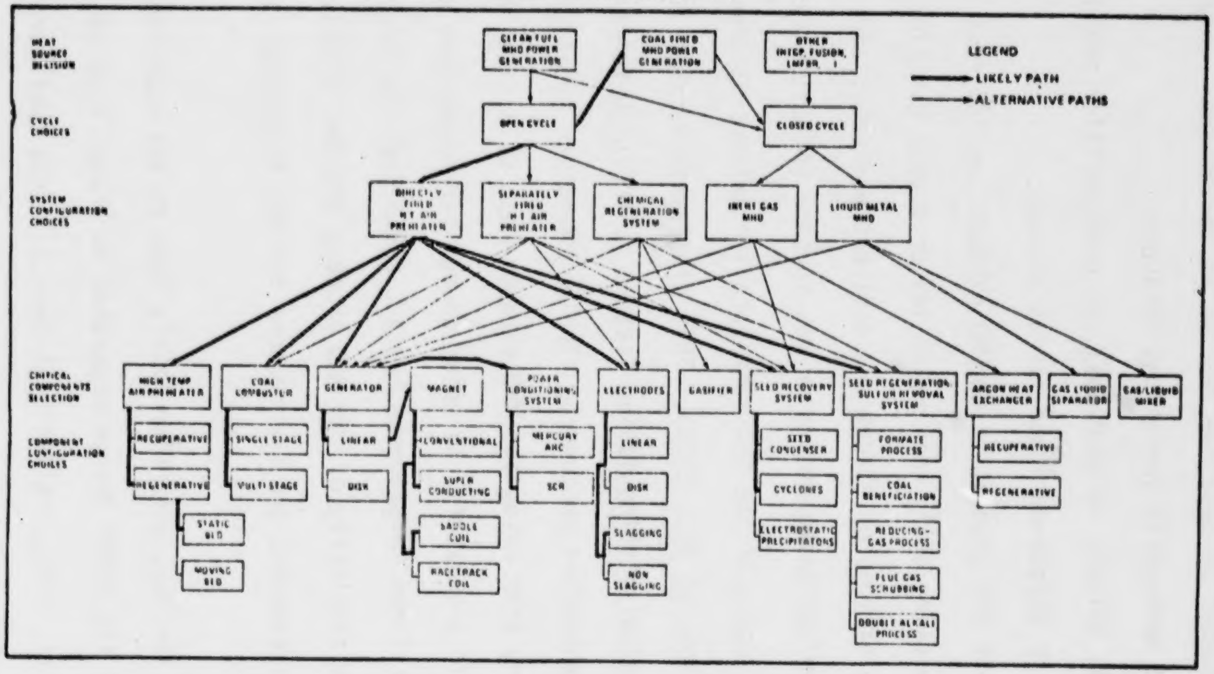

HEAT SOURCE DECISION
CYCLE CHOICES
SYSTEM CONFIGURATION CHOICES
CRITICAL COMPONENTS SELECTION
COMPONENT CONFIGURATION CHOICES
CLEAN FUEL MHD POWER GENERATION
COAL FIRED MHD POWER GENERATION
OTHER (NUCL. FUSION, LMFBR,)
LEGEND
LIKELY PATH
ALTERNATIVE PATHS
OPEN CYCLE
CLOSED CYCLE
DIRECTLY FIRED HT AIR PREHEATER
SEPARATELY FIRED HT AIR PREHEATER
CHEMICAL REGENERATION SYSTEM
INERT GAS MHD
LIQUID METAL MHD
HIGH TEMP AIR PREHEATER
RECUPERATIVE
REGENERATIVE
STATIC BED
MOVING BED
COAL COMBUSTOR
SINGLE STAGE
MULTI STAGE
GENERATOR
LINEAR
DISK
MAGNET
CONVENTIONAL
SUPER CONDUCTING
SADDLE COIL
RACETRACK COIL
POWER CONDITIONING SYSTEM
MERCURY ARC
SCR
ELECTRODES
LINEAR
DISK
SLAGGING
NON SLAGGING
GASIFIER
SEED RECOVERY SYSTEM
SEED CONDENSER
CYCLONES
ELECTROSTATIC PRECIPITATORS
SEED REGENERATION SULFUR REMOVAL SYSTEM
FORMATE PROCESS
COAL BENEFICIATION
REDUCING-GAS PROCESS
FLUE GAS SCRUBBING
DOUBLE ALKALI PROCESS
ARGON HEAT EXCHANGER
RECUPERATIVE
REGENERATIVE
GAS LIQUID SEPARATOR
GAS/LIQUID MIXER

Figure 3-1 MHD System Decision Tree (Jackson,et al.,1976)

psi/1000°F/1000°F) steam bottoming cycle. In this system the coal processor feeds dried crushed coal to a single-stage cyclone combustor. The preheated air is mixed with the coal at a 95% stiochiometric air fuel ratio and is fired to 2700 K (4400°F). The cyclone combustor is assumed to remove 80% of the coal ash. Potassium carbonate is the seeding material. The MHD generator conditions (Beecher, et al., 1976) include a .62MPa (6 atm) pressure, .75 Mach flow rate, and 6 T magnetic field (in the equivalent Westinghouse ECAS Base Case). The MHD exhaust is at 1650 K (2511°F) and passes to the steam generator. Seed-ash is collected on the superheater surface and in the stack gas cleanup system. The seed is recycled through a Claus plant that converts part of the potassium sulfate to potassium carbonate before reuse. These are the most important features of the frontrunning configuration, additional important parameters are listed in Section 3.1.

3.1 Operating and Design Parameters

Even given the exact design configuration there is still a significant variation in system performance that is due to variations in operating and design parameters. For example, the air preheat temperature can play a major role in system efficiency and cost, and values of 1089 K, 1366 K, 1589 K, 1644 K, 1922 K, and 2200 K (1500°F. 2000°F, 2400°F, 2500°F, 3000°F, and 3500°F) have been explicitly investigated. This section begins with a listing of the important operating and design parameters, Table 3.1-1. This list is separated into the parameters related to the various system components, and is further segregated into the independent parameters and the

TABLE 3.1-1

MAJOR PARAMETERS DETERMINING OCMHD PERFORMANCE

MHD Generator

Independent Parameters

- generator type and channel connection; linear Faraday, Hall, diagonal wall, and cylindrical configurations
- generator size and geometry
- materials
- temperatures and pressures
- working fluid
- magnetic flux density
- seed type and feed rate
- flow rate

Dependent Parameters

- enthalpy extraction ratio
- plasma flow rate
- electrical conductivity of fluid
- electron affinities of OH, CO_2 and AlO_2
- electron-atom collision cross sections
- emissions
- power output
- Hall parameter nonuniformities
- pressure drop
- electrical loading parameter
- heat leak fraction
- enthalpy

Fuel and Combustor

Independent Parameters

- combustor type, design and stages
- combustor pressure and temperature-time history
- coal feed rate and configuration
- coal type and size, or solvent refined or gasified coal characteristics
- oxidizer type and feed rate
- air feed rate and temperature
- coal properties; ash, volatiles, moisture and so on
- drying of coal

Dependent Parameters

- air/fuel ratio
- percent slag rejection
- percent ash in flue gas
- coal moisture
- enthalpy
- pressure drop
- radioactive heat loss
- overall efficiency of combustor
- combustor residence time
- carbon burnout
- uniformity of product distribution

TABLE 3.1-1 (continued)

MAJOR PARAMETERS DETERMINING OCMHD PERFORMANCE

Nozzle, Diffuser, Inverters, Electrodes, Insulators, Compressor

Independent Parameters
- size and geometry of channel, etc.
- materials
- nozzle area, contour
- pressure and temperatures

Dependent Parameters
- lifetimes
- pressure and temperature drops
- thermal losses
- electrical losses
- diffuser exit temperature
- diffuser recovery factor
- duct wall temperature
- heat transfer coefficients
- nozzle heat loss
- channel loft
- efficiencies
- enthalpy
- flow rates

Magnets

Independent Parameters
- magnet size and strength
- support
- magnet shape and orientation

Dependent Parameters
- bending stress
- magnetic flux density

Air Preheater

Independent Parameters
- design and type
- temperatures at stages
- pressure

Dependent Parameters
- lifetime
- air preheater losses
- enthalpy
- pressure drop

TABLE 3.1-1 (continued)

MAJOR PARAMETERS DETERMINING OCMHD PERFORMANCE

Seed and Slag Recovery

Independent Parameters
- combustor designs
- reactor, absorption tower, heat exchanger types and sizes
- coal propertes

Dependent Parameters
- recovery percent
- seed form
- cost and energy losses

Seed Regenerator

Independent Parameters
- reducing process
- design and type

Dependent Parameters
- efficiency and cost
- seed form

Steam Cycle

Independent Parameters
- type and design
- pressures and temperatures
- heat rejection type

Dependent Parameters
- boiler lifetimes
- heat rejection
- heat transfer coefficients
- power turbine heat rate
- compressor turbine heat rate
- power output

dependent parameters, that is those values that can only be controlled through changes in independent parameters. It should be noted that dependent parameters for some components are independent choices for others.

The values for many of the parameters that are expected to be selected for the first commercial design are shown in Table 3.1-2. The Base Case ECAS OCMHD cycle parameters for (Phase I General Electric) are shown in Table 3.1-3. A comparison of major features of the Base Case with the solvent refined coal case is shown in Table 3.1-4; a comparison of magnet designs in Table 3.1-5 and 3.1-6; and a comparison of preheaters in Tables 3.1-7 and 3.1-8.

Phase I ECAS Base Cases for General Electric and Westinghouse are compared to the General Electric Phase III Base Case in Table 3.1-9. Additional Phase II OCMHD Base Case parameters are shown in Table 3.1-10 and performances in 3.1-11. Finally some interesting miscellaneous performance factors are collected in Table 3.1-12.

3.2 Mass Balances of Specific Designs

First it should be reiterated that no large coal-fired OCMHD's are operational. Mass balance computations to date have therefore been calculated analytically not empirically. Computer programs for these computations exist at Westinghouse, General Electric, and elsewhere, and are also being developed at MIT. Thus there is no reason to duplicate these efforts for this study, instead some already published mass balances of important specific OCMHD designs are presented here.

Table 3.1-2 Input Parameters Projected for First Commercial Sized Facility (Jackson, et al., 1976)

POWER INPUT - GROSS	2000 MWth
COMBUSTION	
Coal	Montana, Rosebud Seam
Combustor	Direct, 2-stage, 90% slag-rejection
Seed rate	K - 1% of total combustion products
PREHEATER	
Type	Direct fired, regenerative
Oxidizer temp. (K)	1644
MHD GENERATOR	
Type	Diagonal connected, 15 meter nominal
Load factor	0.7 (variable)
Magnet	Maximum field 6 tesla, superconducting
Flow	High subsonic
DIFFUSER	
Exit pressure (psia)	16.25
Recovery factor	0.8
STEAM BOTTOMING CYCLE	
Steam conditions	3500 psia (1000°F/1000°F)
Heat rejection	wet cooling tower
ENVIRONMENTAL EFFECTS	
SO_2	< 1.2 lb/10^6 Btu
NO_x	< 0.7 lb/10^6 Btu
Particulates	< 0.1 lb/10^6 Btu

Table 3.1-3 Major System Parameters for Open Cycle MHD General Electric Base Case (Harris, Shah, 1976)

		PARAMETER	VALUE OR DESCRIPTION
FUEL COAL			
		TYPE	ILL #6, 10788 Btu/LB HHV
		SIZE, PULVERIZED	70% THROUGH 200 MESH
		MOISTURE CONTENT, DRIED	2%
		OXIDIZER	AIR
FURNACE, GASIFIER OR FUEL PROCESSING			
		COMBUSTOR TYPE	SPECIAL
		COMBUSTION PRESSURE (ATM)	9
		COMBUSTION TEMPERATURE (°F)	4634
		AIR PREHEAT TEMPERATURE	2500
		F/A RATIO RELATIVE TO STOICHIOMETRIC F/A	1.07
		SLAG REJECTION	85%
PRIME CYCLE MHD			
		TYPE	DIAGONAL
		WORKING FLUID	COMBUSTION GASES
		AVERAGE MAGNETIC FLUX DENSITY (TESLA)	5
		COMPRESSOR PRESSURE RATIO	10.75
		DIFFUSER OUTLET PRESSURE (ATM)	1.14
		ELECTRIC LOAD PARAMETER	0.80
		POTASSIUM SEEDING	1%
HEAT EXCHANGER(S)			
	HIGH TEMPERATURE AIR HEATER		
		TYPE	REFRACTORY CERAMIC STORAGE
		GAS $\Delta P/P$	0.07
		AIR $\Delta P/P$	0.02
	RADIANT FURNACE		
		GAS $\Delta P/P$	0.01
		WATER ΔP (PSI)	570
	SECONDARY FURNACE		
		GAS $\Delta P/P$	0.03
		STEAM ΔP (PSI)	854
		AIR ΔP (PSI)	21
	ECONOMIZERS		
		GAS $\Delta P/P$	0.02
		WATER ΔP (PSI)	21
STEAM BOTTOMING CYCLE			
	TYPE		3500psi/1000F/1000F
	HEAT RATE FOR POWER TURBINE (BTU/kW-HR)		8160 ($\eta = 42$)
	HEAT RATE FOR COMPRESSOR TURBINE (BTU/kW-HR)		8270 ($\eta = 41$)
	CONDENSING PRESSURE (IN. Hg)		2.3 (106°F)
HEAT REJECTION			
	WET MECHANICAL DRAFT COOLING TOWERS		25 CELLS
	STACK GAS TEMPERATURE		251°F

Table 3.1-4 Summary of Important Parameters for ECAS OCMHD Cases (General Electric,1976)

Base Case

CYCLE PARAMETER

Power Output (MWe)	1932
Combustion	
Coal	Solvent refined coal
Oxidizer	Air
Combustor slag rejection (percent)	0
Preheater	
Firing	Direct
Oxidizer temperature (°F)	3100
MHD Generator	
Type	Faraday
Inlet pressure (atm)	15
Average magnetic field (T)	6
Potassium seed (percent)	1.0
Electrical load parameter	0.8
Heat Exchangers	
Gas (Δp/p)	0.15
Air (Δp/p)	0.10
Steam Bottoming Cycle	
Turbine inlet temperature (°F)	1000/1000
Turbine inlet pressure (psi)	3500
Maximum feedwater temperature (°F)	232
Air Bottoming Cycle	
Turbine inlet temperature (°F)	--
Pressure ratio	--
Heat Rejection	Wet cooling tower

MAJOR COMPONENT CHARACTERISTICS

Major Component	Unit or Module Size (ft) (W x L (or D) x H)	Weight (lb) (x 10⁶)	Cost ($ x 10⁶)	Units Required	Total Cost ($ x 10⁶)	$/kW Output
Combustor	5.7 dia x 11 long	0.022	2.2	1	2.20	1.14
Nozzle/generator/diffuser	Inlet area 22 m^2 Exit area 4100 m^2 } x 250 long	2.92	7.90	1	7.90	4.09
Magnet and dewar	44 dia x 91 long	9.0	43.00	1	43.00	22.26
Radiant furnace	80 x 58.5 x 100	0.76	2.44	1	2.44	1.26
Superheater/reheater	80 x 36.5 x 56.2	8.04	19.91	1	19.91	10.31
Economizer	80 x 28.8 x 6.1	1.50	1.13	1	1.13	0.58
High temperature air heater	34 dia x 75 high	5.29	2.67	6	16.00	8.28
Low temperature air heater	80 x 29.0 x 26.4	2.61	10.75	1	10.75	5.56
Seed recovery system	--	--	1.00	1	1.00	0.52
Steam turbine generator set	30 x 174 x 25	4.30	12.90	1	12.90	6.68
Inverters	--	--	97.40	1	97.40	50.41

SRC Base Case

CYCLE PARAMETER

Power Output (MWe)	1895
Combustion	
Coal	Illinois No. 6
Oxidizer	Air
Combustor slag rejection (percent)	90
Preheater	
Firing	Direct
Oxidizer temperature (°F)	2500
MHD Generator	
Type	Faraday
Inlet pressure (atm)	9
Average magnetic field (T)	5
Potassium seed (percent)	1.0
Electrical load parameter	0.8
Heat Exchangers	
Gas (Δp/p)	0.15
Air (Δp/p)	0.10
Steam Bottoming Cycle	
Turbine inlet temperature (°F)	1000/1000
Turbine inlet pressure (psi)	3500
Maximum feedwater temperature (°F)	232
Air Bottoming Cycle	
Turbine inlet temperature (°F)	--
Pressure ratio	--
Heat Rejection	Wet cooling tower

MAJOR COMPONENT CHARACTERISTICS

Major Component	Unit or Module Size (ft) (W x L (or D) x H)	Weight (lb) (x 10⁶)	Cost ($ x 10⁶)	Units Required	Total Cost ($ x 10⁶)	$/kW Output
Combustor	9 dia x 27 long	0.051	5.00	1	5.00	2.64
Nozzle/generator/diffuser	Inlet area 22 m^2 Exit area 4100 m^2 } 250 long	2.92	7.90	1	7.90	4.17
Magnet and dewar	44 dia x 100 long	8.20	44.00	1	44.00	23.22
Radiant furnace	80 x 60 x 100	0.98	3.15	1	3.15	1.66
Superheater/reheater	80 x 38.7 x 70	9.50	22.72	1	22.72	11.99
Economizer	80 x 32.7 x 7.9	2.20	1.64	1	1.64	0.87
High-temperature air heater	34 dia x 75 high	4.85	2.07	6	12.4	6.54
Low-temperature air heater	80 x 36.5 x 29.6	3.30	12.26	1	12.26	6.47
Seed recovery system	--	--	[illegible]	1	8.00	4.22
Steam turbine-generator set	30 x 174 x 25	4.5	20.0	1	20.08	10.55
Inverters	--	--	86.60	[illegible]	86.60	45.70

Table 3.1-5 Magnet Design Data for Base Case MHD Generator
Case 1 - 2000MWE Plant Size
(General Electric, 1976)

Channel Specifications

Inlet		1.4297 m × 1.4297 m
Exit		3.653 m × 3.653 m
Active Length		25m
Field:	Inlet	2.496 T
	Bo max.	5.992 T
	Exit	3.12 T
$VB^2 = \int_0^{25} AB^2\,dl$		$11{,}600\ m^3T^2$

Magnet Design Data

Warm bore (circular)	Inlet	2.87 m
	Exit	6.50 m
Active length		25 m
Ampere turns		50.8×10^6
Ampere meters		34.2×10^8
Stored energy		15,200 megajoules
Current density, winding, average		$2.0 \times 10^7\ A/m^2$
Dewar O.D.		
Inlet end		9.3 m
Exit end		13.6 m
Dewar length, overall		31 m
Conductor weight		900,000 kg
Main structure weight (design stress 25,000 psi)		1,900,000 kg
Internal structure & miscellaneous weight		180,000 kg
Dewar weight		750,000 kg
	Total	3,730,000 kg

Table 3.1-6 Magnet Design Data for Base Case MHD Generator
Case 24 - SRC As Fuel (General Electric, 1976)

Channel Specifications

Inlet	1.067 m sq.
Exit	3.499 m sq.
Active length	∿20 m
Field: Inlet	3.21 T
Peak	7.72 T
Exit	2.40 T

Magnet Design Data

Warm bore (circular):	Inlet	2.60 m
	Exit	6.36 m
Active length		20 m
Field: Inlet		3.2
Peak		7.9
Exit		2.4
$VB^2 = \int_0^{20} AB^2\,dl$		13,200 m^3T^2
Ampere turns		76.4×10^6
Current density, average		2.0×10^7 A/m^2
Dewar O.D.		
Inlet end		9.8 m
Exit end		13.7 m
Dewar length		28 m
Conductor weight		1,036,000 kg
Main structure weight		2,100,000 kg
Intermediate structure & miscellaneous weight		200,000 kg
Dewar weight		750,000 kg
	Total	4,086,000 kg

Table 3.1-7 Air Preheater Design Data for GE OCMHD Cases 1, 2 and 3 (General Electric, 1976)

	Case 1	Case 2	Case 3
Plant Size MWe	2000	1200	600
Air preheat temp (°F)	2500	2500	2500
Air pressure (atm)	10.5	10.5	10.5
Number of Heaters	6 [2 blowdown 3 reheat 1 spare	6 [2 blowdown 3 reheat 1 spare	6 [2 blowdown 3 reheat 1 spare
Heater bed dia. (ft)	30	24	17
Heater bed height (ft)	40	40	40
Heater total height (ft)	75	70	60
Heater bed weight (tons)	1400	900	450
Heater total weight (tons)	2400	1650	1000
Pressure drop			
Air side (atm)	0.01	0.01	0.01
Gas side (atm)	0.06	0.06	0.06

Table 3.1-8 Air Preheater Design Data for GE OCMHD Case 24 - Base Case with SRC As Fuel (General Electric, 1976)

Air preheat temperature (°F)	3100
Air pressure (atm)	16
Number of Heaters	6 [2 blowdown 3 reheat 1 spare
Heater bed diameter (ft)	30
Heater bed height (ft)	40
Heater total height (ft)	75
Heater bed weight (tons)	1600
Heater total weight (tons)	2600
Pressure drop	
Air side (atm)	0.01
Gas side (atm)	0.10

Table 3.1-9 Comparison of Performance Data for Coal/Open Cycle MHD/ Steam Systems Between ECAS Phases 1 and 2 (NASA, 1977)

	Phase 2 G. E. conceptual powerplant	Phase 1	
		Westinghouse base case 2, point 17	G. E. base case 1
Net output power, MWe	1932	1988	1895
Coal thermal input to combustor, MWt	3688	3870	3700
Air preheat temperature, °F	2500	2400	2500
MHD inlet temperature, °F	4634	4503	4634
MHD diffuser exit temperature, °F	3662	3655	3625
MHD inlet pressure, atm	9.0	7.0	9.0
Compressor exit pressure, atm	10.7	7.6	10.5
Airflow, lb/sec:			
Primary	2492	2653	2486
Secondary	189	279	187
MHD inverter output power, MWe	1406	1230	1399
Compressor power required[a], MWe	377	307	361
Steam turbine-generator output, MWe	587	821	555
Powerplant gross power output, MWe	1993	2051	1954
Ratio of the difference of MHD power and compressor power to plant gross power	0.52	0.45	0.53
Auxiliary power required, MWe	50.7	63	55.6
Ratio of auxiliary power to powerplant gross power	0.025	0.031	0.028
Coal thermal input to seed-reprocessing system, MWt	311	213	231
Ratio of coal for seed reprocessing to total coal	0.078	0.052	0.059
MHD efficiency, MHD power minus compressor power divided by amount of coal to combustor	0.279	0.238	0.281
Steam-cycle efficiency (including generator)	0.420	0.420	0.400
Thermodynamic efficiency, ratio of gross power to amount of coal to combustor	0.540	0.530	0.528
Overall efficiency, ratio of net power to total coal used	0.483	0.487	0.483

[a] Given in electric power even if shaft driven.

Table 3.1-10 Major Design Parameters of Coal/Open Cycle MHD/ Steam System - ECAS Phase 2 (NASA, 1977)

Coal type	Illinois #6
Moisture content of coal delivered to combustor, percent	2
Air preheat temperature, °F	2500
Combustion pressure, atm	9
Combustion temperature, °F	4634
Combustor fuel-air ratio relative to stoichiometric	1.07
Combustor slag rejection, percent	85
Slag carryover to channel, percent	15
Generator type	Diagonal wall
Average magnetic flux density, T	5
Electrical load parameter.	0.8
Potassium seed, percent	1
Steam-bottoming-cycle conditions, psig/°F/°F	3500/1000/1000
Cooling tower type.	Wet mechanical draft
Stack-gas temperature, °F	251

Table 3.1-11 Summary of Performance and Cost for Coal/ Open Cycle MHD/Steam System - ECAS Phase 2 (NASA, 1977)

Net powerplant output (60 Hz; 500 kV), MWe	1932.2
Thermodynamic efficiency, percent	54.0
Powerplant efficiency, percent	49.8
Overall energy efficiency, percent	48.3
Coal consumption, lb/kW-hr	0.655
Total wastes, lb/kW-hr	0.082
Powerplant capital cost, dollars	1391.1×10^6
Powerplant capital cost, $/kWe	720.0
Cost of electricity (capacity factor, 0.65), mills/kW-hr:	
Capital	22.7
Fuel	7.3
Operation and maintenance	1.7
Total.	31.8
Estimated time of construction, yr	6.5
G. E. estimate of approximate date of first commercial service	1996-1999

TABLE 3.1-12

PROJECTED OCMHD OPERATING CHARACTERISTICS

Full Load Heat Rate	
(Pomeroy, *et al.*, 1978)	7068 Btu/kWh
(Pepper, Yu, 1974)	6600 Btu/kWh
Forced/Planned Outage Rate	
(Pomeroy, *et al.*, 1978)	20%/15%
(Jackson, *et al.*, 1976)	20% total unavailability
Minimum Load	
(Pomeroy, *et al.*, 1978)	60% full capacity
(Pomeroy, *et al.*, 1978)	85% of full efficiency
Lifetime	
(Beecher, *et al.*, 1976)	30 years

Perhaps the most important design, certainly the most often cited, is the ECAS General Electric Base Case. The first mass and energy balance schematic of this case showed the potential of flexibility of input fuels, Figure 3.2-1. A slightly revised and later version of this schematic is shown in Figure 3.2-2.

The ECAS Phase I Westinghouse equivalent Base Case is shown in the schematic diagram in Figure 3.2-3 (Base Case 2). The other major configurations studied by Westinghouse included a coal gasifier, shown in Figure 3.2-4, and a char fuel option, shown in Figure 3.2-5.

Another important mass and energy schematic is that developed for the U.S. Department of Energy that is to represent the goal for the first commercial facility, see Figures 3.2-6 and 3.2-7.

EPRI has also sponsored mass and energy schematics, and that closest to the ECAS Base Cases is shown in Figure 3.2-8. Figure 3.2-9 shows a scheme for increasing the stiochiometric air ratio to 120%. This cycle is incorporated into the other EPRI-sponsored schematic in Figure 3.2-10 as an attempt to maximize NO_x and extract it as a fixed nitrogen source for fertilizers.

Aside from these system-wide schematics there are a number of mass and energy balances of particular types of components. For example, perhaps the most important of these are the seed regeneration schematics which include the ECAS schematics, Figure 3.2-11, Tables 3.2-1 and 3.2-2, as well as others, Figure 3.2-12, Tables 3.2-3, 3.2-4 and 3.2-5.

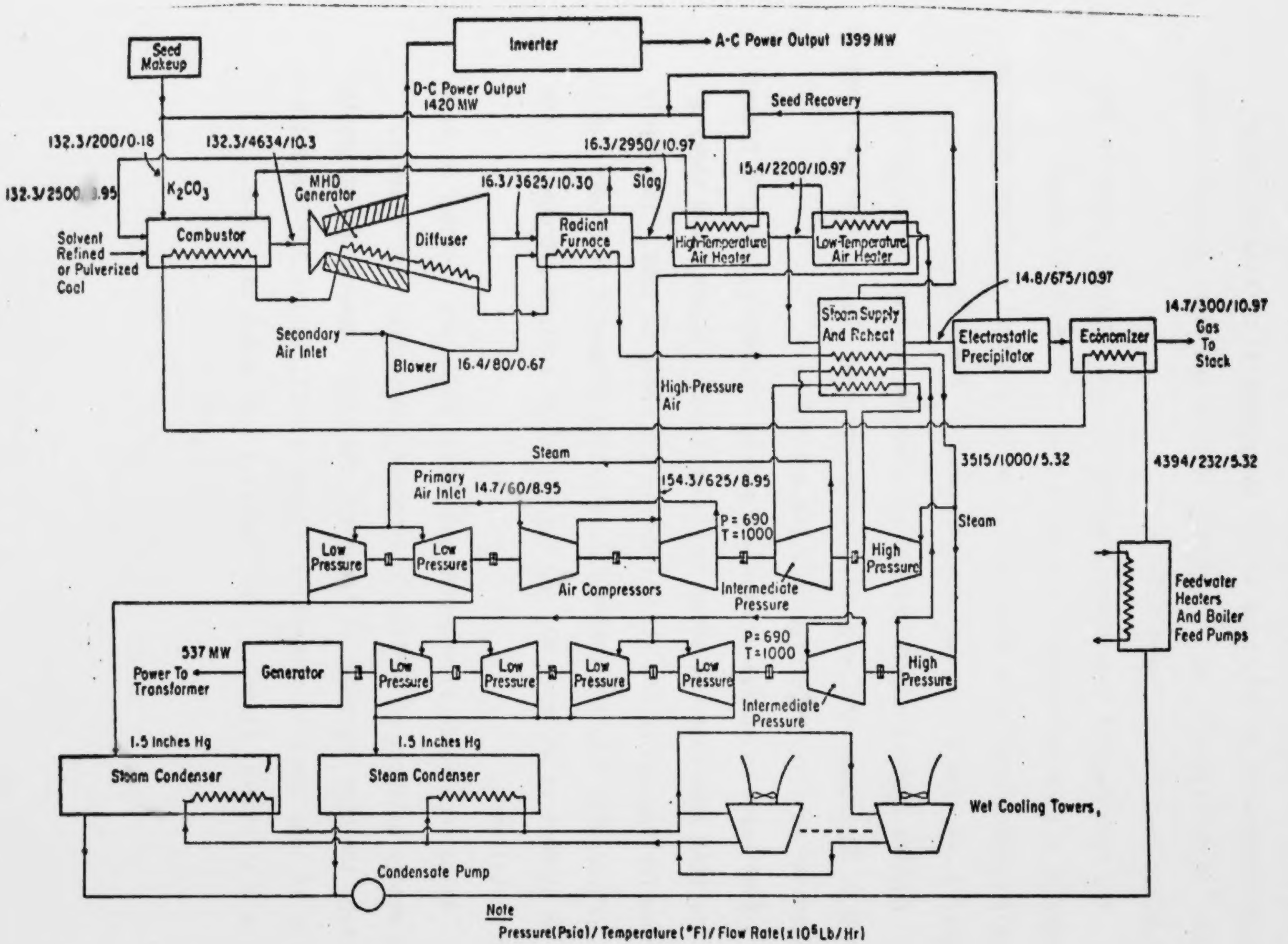

Seed Makeup
Inverter
A-C Power Output 1399 MW
D-C Power Output 1420 MW
Seed Recovery
132.3/200/0.18
132.3/4634/10.3
16.3/2950/10.97
15.4/2200/10.97
132.3/2500 .95
K_2CO_3
MHD Generator
16.3/3625/10.30
Slag
Solvent Refined or Pulverized Coal
Combustor
Diffuser
Radiant Furnace
High-Temperature Air Heater
Low-Temperature Air Heater
14.8/675/10.97
Steam Supply And Reheat
Electrostatic Precipitator
Economizer
14.7/300/10.97
Gas To Stack
Secondary Air Inlet
Blower
16.4/80/0.67
High-Pressure Air
Steam
Primary Air Inlet
14.7/60/8.95
154.3/625/8.95
3515/1000/5.32
4394/232/5.32
P = 690
T = 1000
Steam
Low Pressure
Low Pressure
Air Compressors
Intermediate Pressure
High Pressure
Feedwater Heaters And Boiler Feed Pumps
537 MW
Power To Transformer
Generator
Low Pressure
Low Pressure
Low Pressure
Low Pressure
P = 690
T = 1000
Intermediate Pressure
High Pressure
1.5 Inches Hg
1.5 Inches Hg
Steam Condenser
Steam Condenser
Wet Cooling Towers,
Condensate Pump
Note
Pressure(Psia)/Temperature(°F)/Flow Rate(x10⁶Lb/Hr)

Figure 3.2-1 Open-Cycle MHD for GE ECAS Base Case 1 (General Electric, 1976)

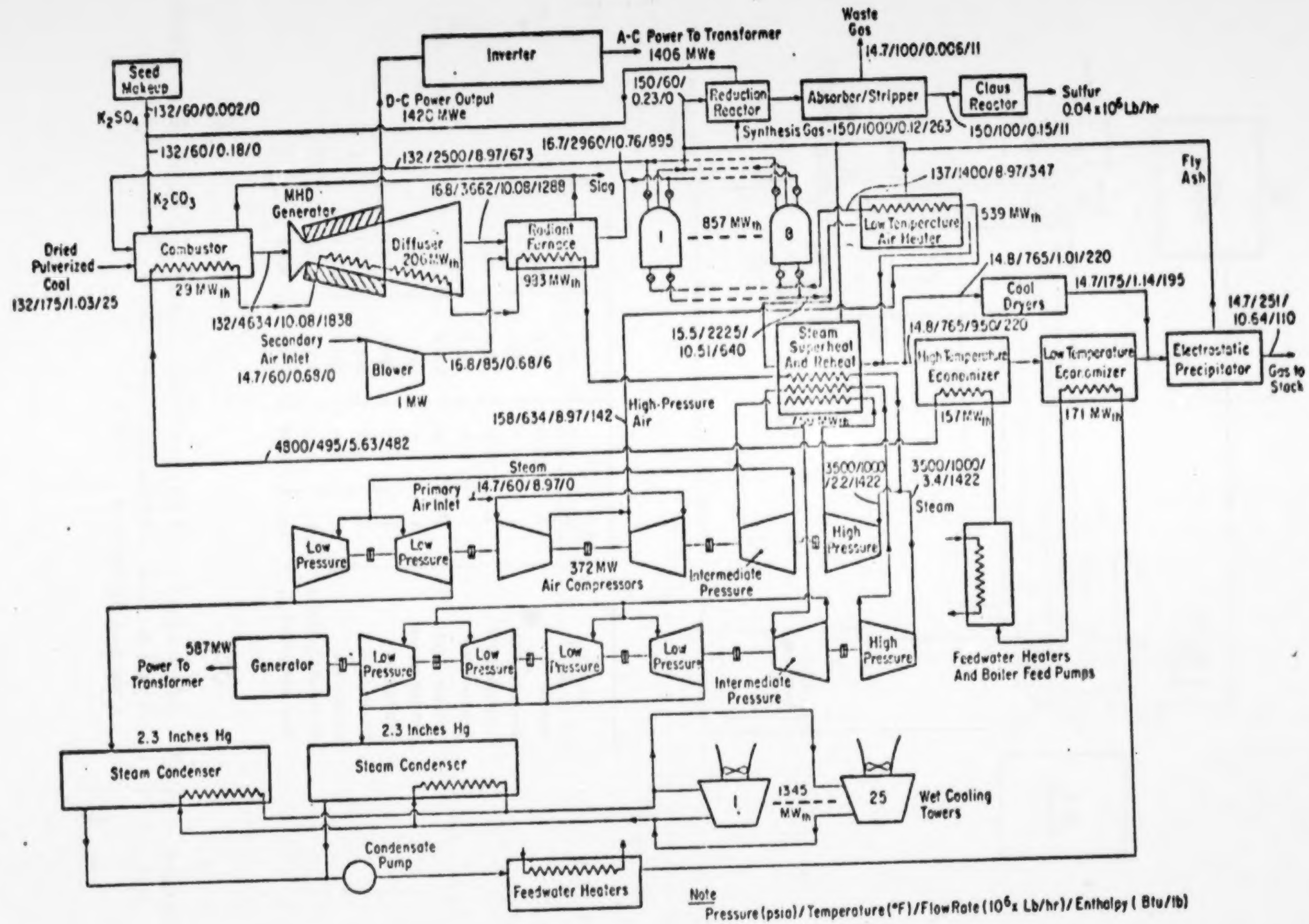
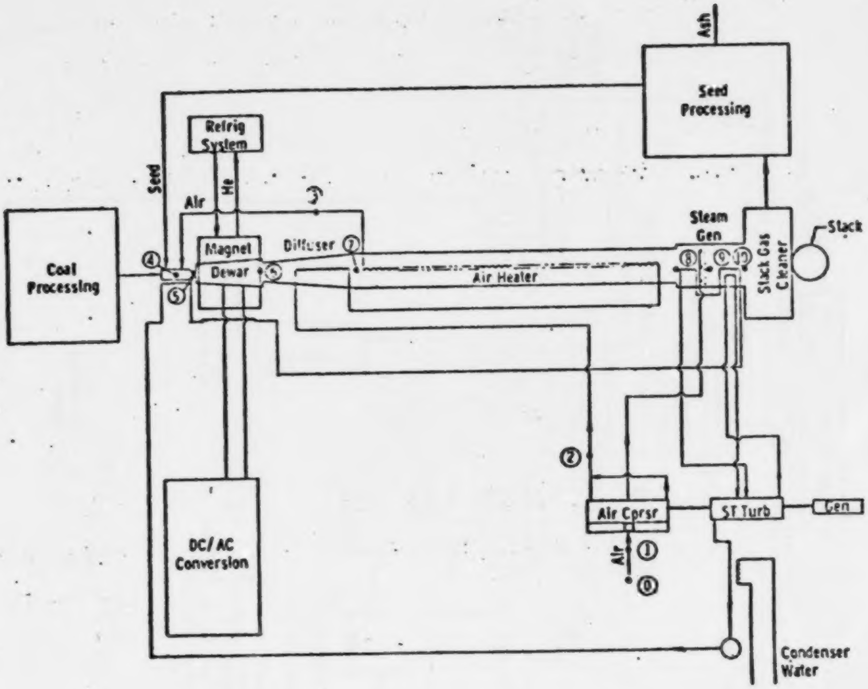

Seed Makeup
K2SO4
132/60/0.002/0
132/60/0.18/0
K2CO3
Dried Pulverized Coal
132/175/1.03/25
Combustor
29 MWth
MHD Generator
Diffuser
206 MWth
132/4634/10.08/1838
Secondary Air Inlet
14.7/60/0.68/0
Blower
1 MW
16.8/85/0.68/6
Inverter
D-C Power Output
1420 MWe
A-C Power To Transformer
1406 MWe
132/2500/8.97/673
16.8/3662/10.08/1288
Slag
Radiant Furnace
933 MWth
16.7/2960/10.76/895
150/60/0.23/0
Reduction Reactor
Synthesis Gas - 150/1000/0.12/263
Absorber/Stripper
Waste Gas
14.7/100/0.006/11
Claus Reactor
150/100/0.15/11
Sulfur
0.04 x 10⁶ Lb/hr
1
857 MWth
8
137/1400/8.97/347
Low Temperature Air Heater
539 MWth
Fly Ash
14.8/765/1.01/220
Coal Dryers
14.7/175/1.14/195
14.7/251/10.64/110
Electrostatic Precipitator
Gas to Stack
15.5/2225/10.51/640
Steam Superheat And Reheat
14.8/765/950/220
High Temperature Economizer
157 MWth
Low Temperature Economizer
171 MWth
High-Pressure Air
158/634/8.97/142
4800/495/5.63/482
Steam
Primary Air Inlet
14.7/60/8.97/0
Low Pressure
Low Pressure
372 MW
Air Compressors
Intermediate Pressure
High Pressure
3500/1000/22/1422
3500/1000/3.4/1422
Steam
Feedwater Heaters And Boiler Feed Pumps
587 MW
Power To Transformer
Generator
Low Pressure
Low Pressure
Low Pressure
Low Pressure
Intermediate Pressure
High Pressure
2.3 Inches Hg
Steam Condenser
2.3 Inches Hg
Steam Condenser
1
1345 MWth
25
Wet Cooling Towers
Condensate Pump
Feedwater Heaters
Note
Pressure (psia) / Temperature (°F) / Flow Rate (10⁶ x Lb/hr) / Enthalpy (Btu/lb)

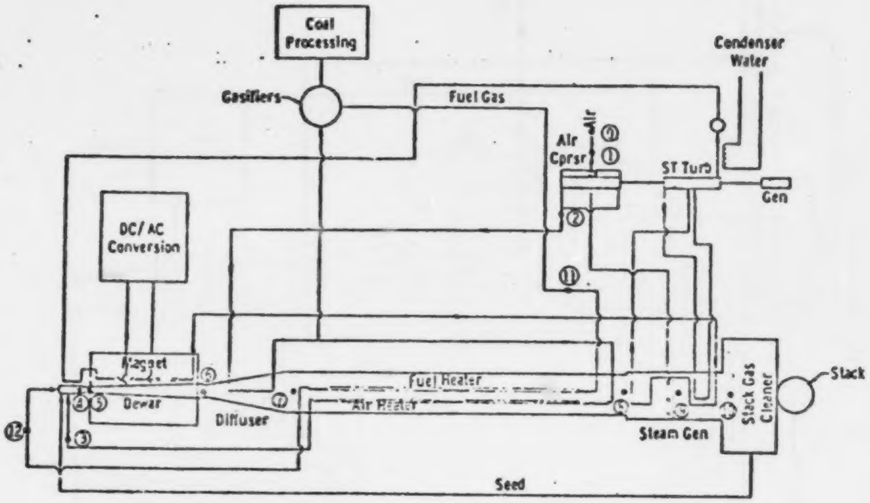
Figure 3.2-2 Later Schematic Diagram of ECAS Base Case Open Cycle MHD (General Electric, 1976)



Ash
Seed Processing
Refrig System
Seed
Air
He
③
Coal Processing
④
⑤
Magnet
Dewar
⑥
Diffuser
⑦
Air Heater
Steam Gen
⑧
⑨
⑩
Stack Gas Cleaner
Stack
②
DC/AC Conversion
Air Cprsr
ST Turb
Gen
Air
①
⓪
Condenser Water

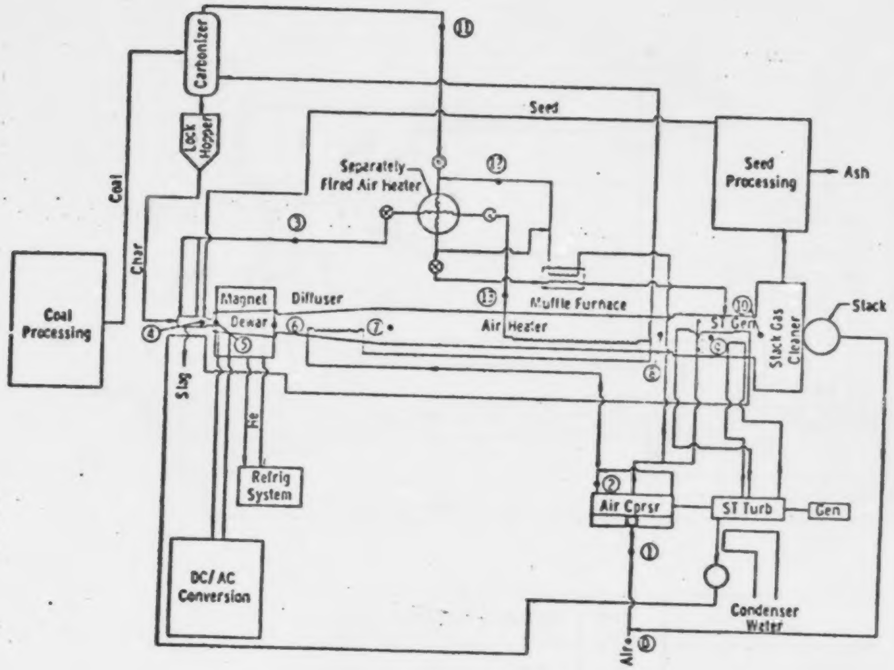
Location	Point No.	Pressure, Psia	Temperature, °F	Flow, lb/s
Ambient	0	14.696	59.0	2768.5
Compressor Inlet	1	14.40	59.0	2768.5
Compressor Outlet	2	95.36	465.2	2768.5
Preheater Outlet	3	92.58	2398.4	2768.5
Combustor Outlet	4	88.18	4414.4	3144.3
MHD Duct Entrance	5	59.18	4155.8	3144.3
MHD Duct Exit	6	13.09	3460.4	3144.3
Diffuser Exit	7	17.00	3644.0	3144.3
Preheater Exit	8	16.52	2538.0	3435.8
Air Quench Chamber Exit	9	15.58	1853.0	3435.8
Steam Generator Exit	10	14.696	305.0	3435.8

Figure 3.2-3 Schematic Diagram and State Points for Open Cycle MHD Westinghouse ECAS Base Case 2 (Westinghouse, 1976)


Coal Processing
Gasifiers
Fuel Gas
Condenser Water
Air
⓪
Air Cprsr
①
ST Turb
Gen
②
DC/AC Conversion
⑪
Magnet
⑥
Fuel Heater
④ ⑤
Dewar
⑦
Air Heater
Diffuser
⑧
⑨
⑩
Stack Gas Cleaner
Stack
⑫
③
Steam Gen
Seed

Location	Point No.	Pressure, Psia	Temperature, °F	Flow, lb/s
Ambient	0	14.696	59.0	1710.2
Compressor Inlet	1	14.40	59.0	1710.2
Compressor Outlet	2	158.94	603.8	1710.2
Air Preheater Outlet	3	154.31	2587.4	1710.2
Combustor Outlet	4	146.96	4400.0	3030.2
MHD Duct Entrance	5	99.02	4119.6	3030.2
MHD Duct Exit	6	13.54	3280.4	3030.2
Diffuser Exit	7	17.00	3446.0	3030.2
Air Preheater Exit	8	16.52	2230.4	3210.2
Air Quench Chamber Exit	9	15.58	1652.0	3210.2
Steam Generator Exit	10	14.696	305.0	3210.2
Fuel Preheater Entrance	11	158.90	1600.0	1282.9
Fuel Preheater Exit	12	154.31	2591.0	1282.9

Figure 3.2-4 Schematic Diagram and State Points for Open Cycle MHD Westinghouse ECAS Base Case 3 (Westinghouse, 1976)


⑪
Carbonizer
Lock Hopper
Coal
Char
Seed
Seed Processing
Ash
Separately Fired Air heater
⑫
③
Coal Processing
Magnet
Dewar
Diffuser
④
⑤
⑥
⑦
⑬
Muffle Furnace
Air Heater
⑩
ST Gen
⑨
⑧
Stack Gas Cleaner
Stack
Slag
He
Refrig System
②
Air Cprsr
ST Turb
Gen
①
DC/AC Conversion
Condenser Water
Air
⓪

Location	Point No.	Pressure, Psia	Temperature, °F	Flow, lb/s
Ambient	0	14.696	59.0	1976.3
Compressor Inlet	1	14.40	132.1	2934.7
Compressor Outlet	2	95.36	54.69	2934.7
Air Preheater Outlet	3	92.58	2933.5	2934.7
Combustor Outlet	4	88.18	4400.0	3194.8
MHD Duct Entrance	5	58.59	4162.4	3194.8
MHD Duct Exit	6	12.94	3422.6	3194.8
Diffuser Exit	7	17.00	3620.6	3194.8
Air Preheater Exit	8	16.52	2453.0	3194.8
Air Quench Chamber Exit	9	15.58	1550.0	3493.4
Steam Generator Exit	10	14.696	305.0	3493.4
Gapor	11	16.16	800.0	113.0
SFA Combustion Air	12	21.25	2384.0	632.0
Cross-over Air	13	93.5	2384.0	2934.7

Figure 3.2-5 Schematic Diagram and State Points for Open Cycle MHD Westinghouse ECAS Base Case 1 (Hoover, et al., 1976)

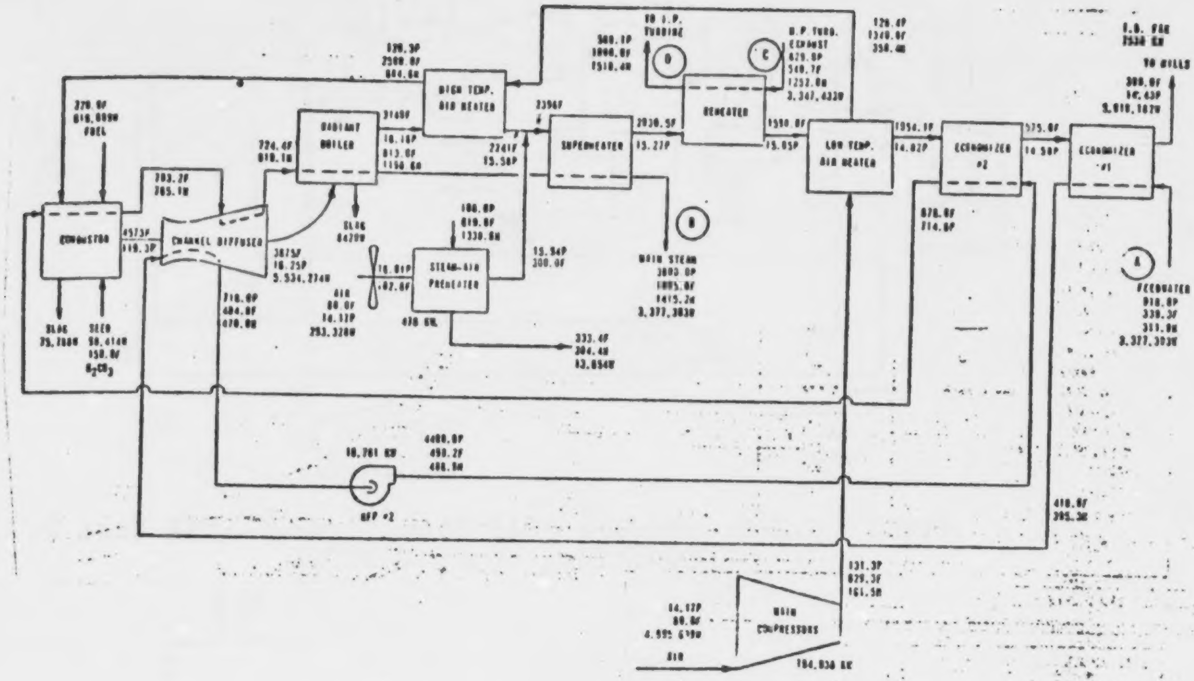

TO I.P. TURBINE
H.P. TURB. EXHAUST
HIGH TEMP. AIR HEATER
RADIANT BOILER
FUEL
COMBUSTOR
CHANNEL DIFFUSER
SUPERHEATER
REHEATER
LOW TEMP. AIR HEATER
ECONOMIZER #2
ECONOMIZER #1
TO MILLS
I.D. FAN
STEAM-AIR PREHEATER
AIR
SLAG
SEED
MAIN STEAM
FEEDWATER
BFP #2
MAIN COMPRESSORS
A
B
C
D

Figure 3.2-6 Air-Gas Side Balance of OCMHD (Jackson, et al., Oct, 1976)

LEGEND:
H - ENTHALPY - BTU/LB
W - FLOW - LB/HR
P - PRESSURE - PSIA
F - TEMPERATURE - F DEGREES

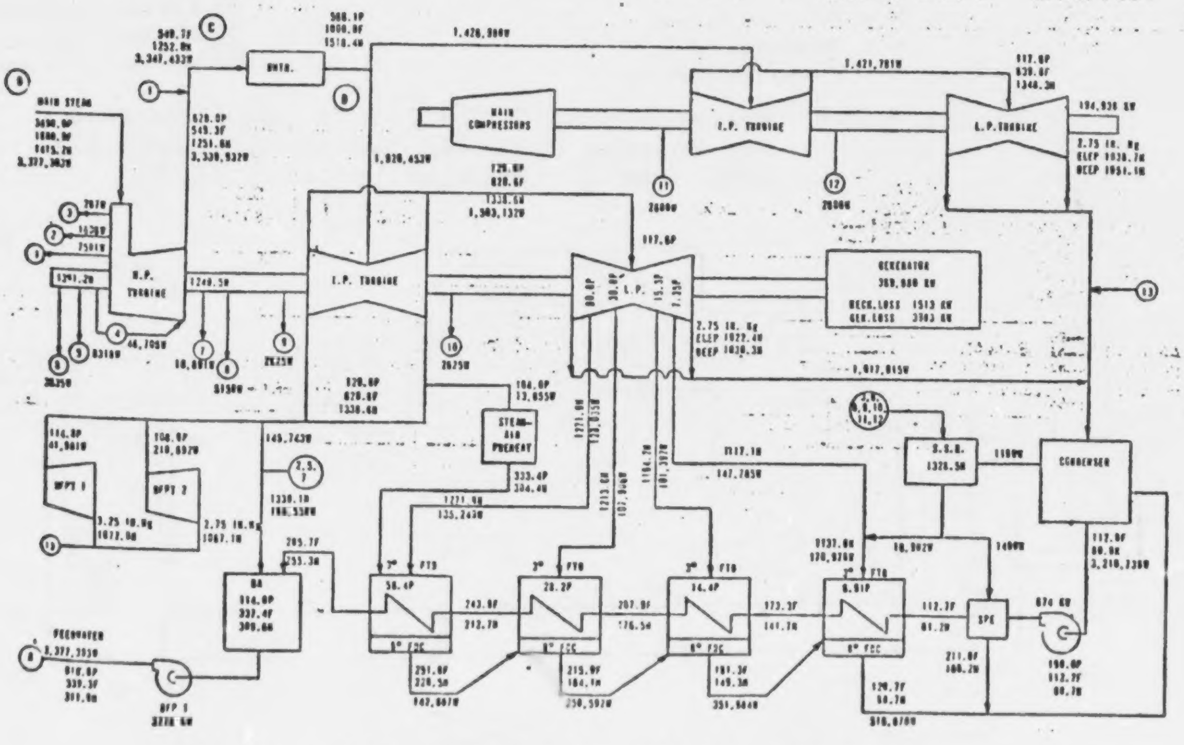

C
B
D
MAIN STEAM
RHTR.
MAIN COMPRESSORS
I.P. TURBINE
L.P. TURBINE
H.P. TURBINE
I.P. TURBINE
L.P.
GENERATOR
369,980 KW
MECH. LOSS 1513 KW
GEN. LOSS 3303 KW
STEAM-AIR PREHEAT
S.S.R.
CONDENSER
BFPT 1
BFPT 2
DA
FEEDWATER
BFP 1
SPE
7° FTD
5° FTD
3° FTD
2° FTD
8° FDC

Figure 3.2-7 Steam Side Balance of OCMHD (Jackson, et al., Oct. 1976)

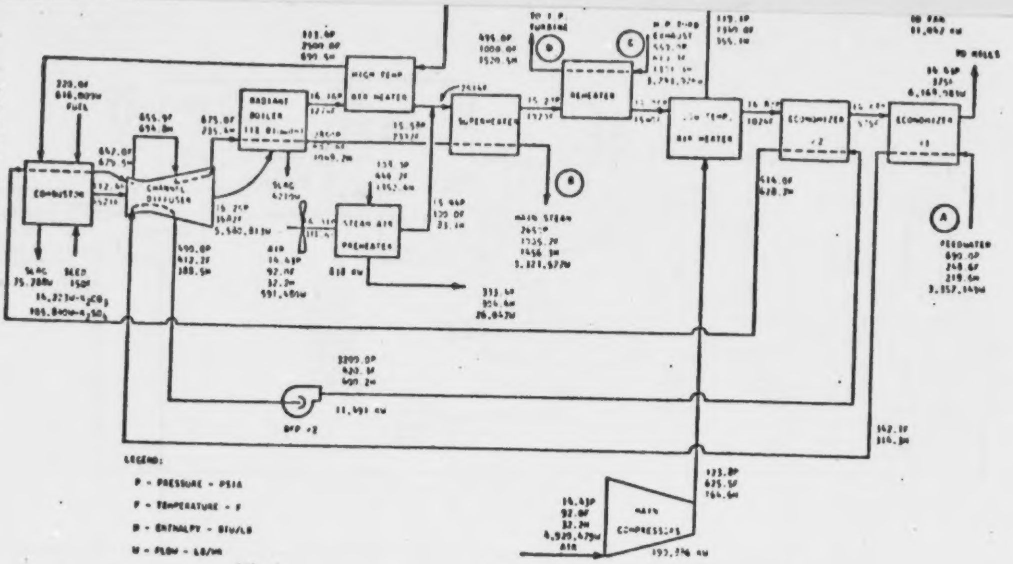

COMBUSTOR
CHANNEL
DIFFUSER
RADIANT BOILER
HIGH TEMP AIR HEATER
SUPERHEATER
REHEATER
LOW TEMP. AIR HEATER
ECONOMIZER #2
ECONOMIZER #1
STEAM AIR PREHEATER
MAIN COMPRESSORS
FUEL
SLAG
SEED
AIR
MAIN STEAM
FEEDWATER
TO I.P. TURBINE
H.P. TURB EXHAUST
TO FAN
TO MILLS
BFP #2
Ⓐ
Ⓑ
Ⓒ
Ⓓ
LEGEND:
P - PRESSURE - PSIA
F - TEMPERATURE - F
H - ENTHALPY - BTU/LB
W - FLOW - LB/HR

Figure 3.2-8 Air-Gas Side Flow Diagram-EPRI Case 2 (Cutting, et al., 1977)

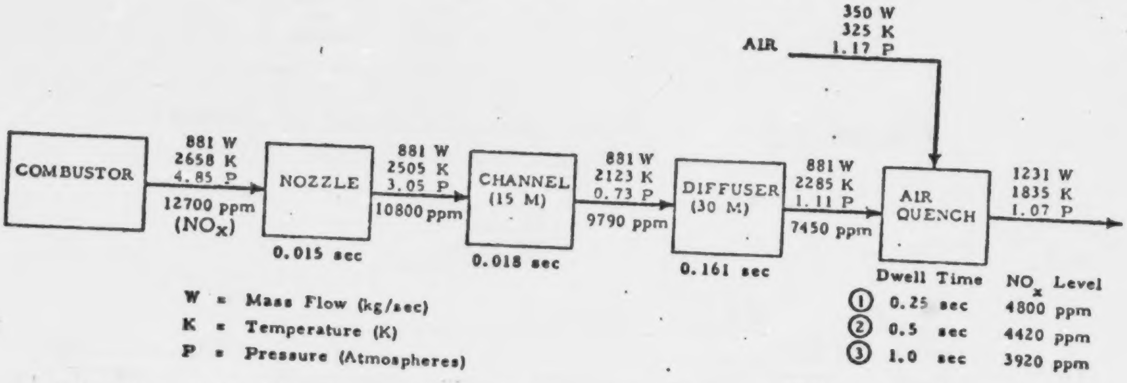

AIR
350 W
325 K
1.17 P
COMBUSTOR
881 W
2658 K
4.85 P
12700 ppm
(NOx)
NOZZLE
0.015 sec
881 W
2505 K
3.05 P
10800 ppm
CHANNEL
(15 M)
0.018 sec
881 W
2123 K
0.73 P
9790 ppm
DIFFUSER
(30 M)
0.161 sec
881 W
2285 K
1.11 P
7450 ppm
AIR QUENCH
1231 W
1835 K
1.07 P
W = Mass Flow (kg/sec)
K = Temperature (K)
P = Pressure (Atmospheres)
Dwell Time
NOx Level
① 0.25 sec 4800 ppm
② 0.5 sec 4420 ppm
③ 1.0 sec 3920 ppm

Figure 3.2-9 Thermodynamic State Points and Flowrates for Topping Cycle-120% Stoichiometric Air EPRI Case 4 (Cutting, et al., 1977)

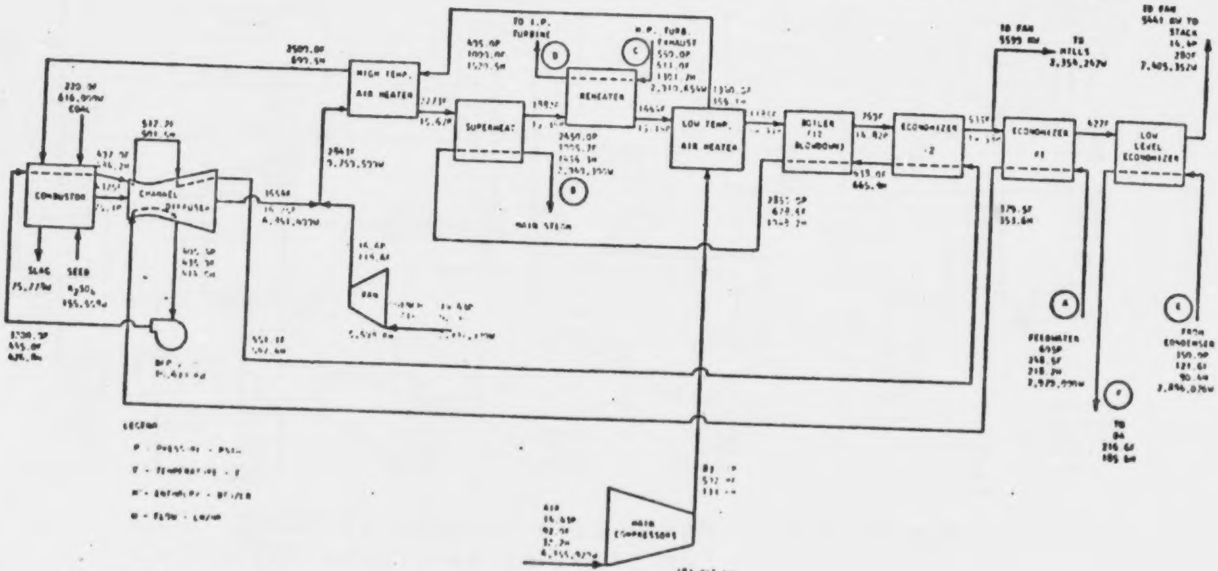

COMBUSTOR
CHANNEL
DIFFUSER
HIGH TEMP. AIR HEATER
SUPERHEAT
REHEATER
LOW TEMP. AIR HEATER
BOILER
BLOWDOWN
ECONOMIZER #2
ECONOMIZER #1
LOW LEVEL ECONOMIZER
FAN
MAIN COMPRESSORS
COAL
SLAG
SEED
AIR
MAIN STEAM
TO I.P. TURBINE
H.P. TURB. EXHAUST
TO FAN
TO MILLS
TO STACK
FEEDWATER
FROM CONDENSER
BFP
Ⓐ
Ⓑ
Ⓒ
Ⓓ
Ⓔ
Ⓕ
LEGEND

Figure 3.2-10 Air-Gas Side Flow Diagram-EPRI Case 4 (Cutting, et al., 1977)

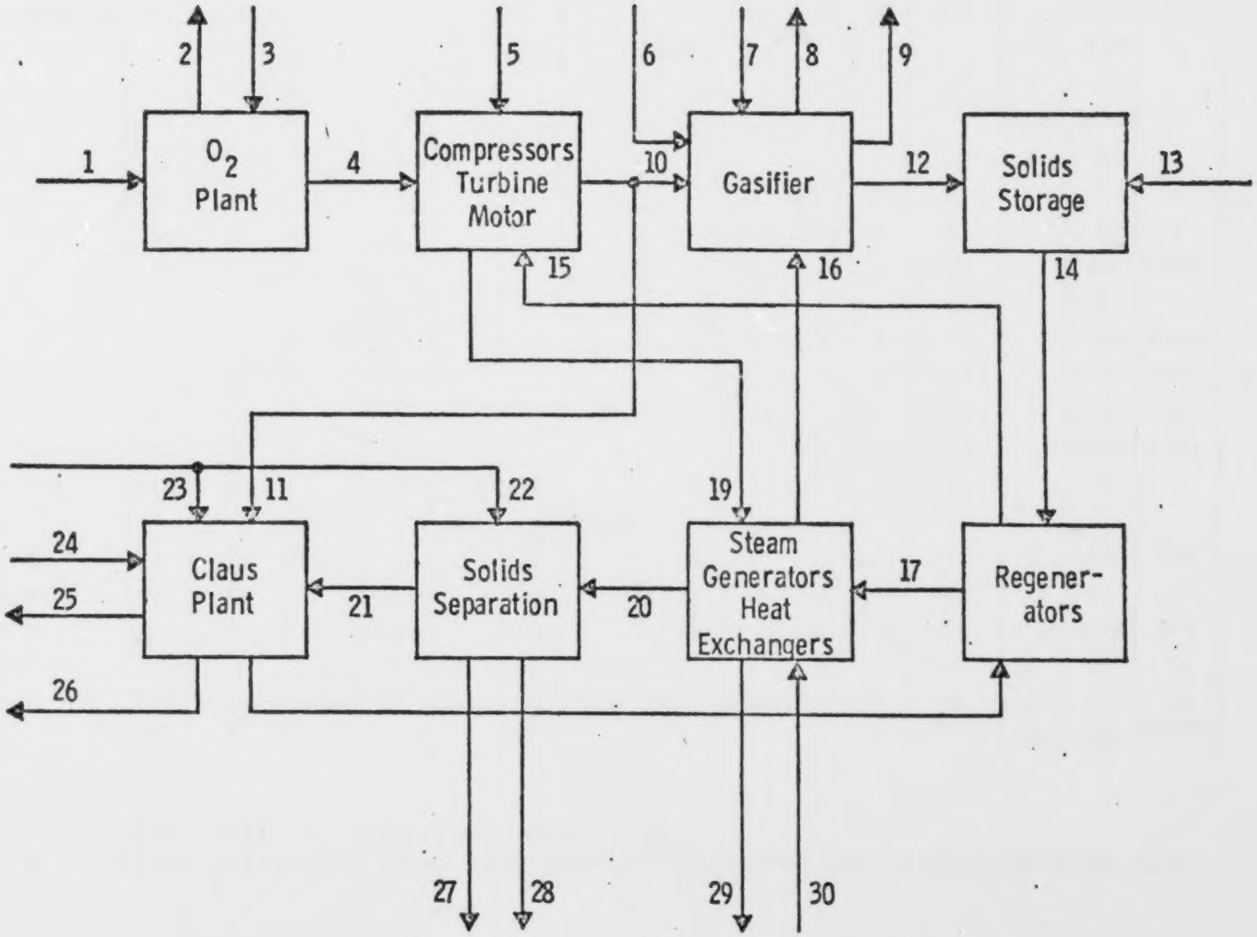

O$_2$ Plant
Compressors Turbine Motor
Gasifier
Solids Storage
Claus Plant
Solids Separation
Steam Generators Heat Exchangers
Regenerators
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
19
20
21
22
23
24
25
26
27
28
29
30

Figure 3.2-11 Simplified Flow Diagram of Seed Regenerative System for Westinghouse ECAS Base Case 2 (Westinghouse, 1976)

Table 3.2-1 Flow Chart for Seed Regeneration System for Westinghouse ECAS Base Case 2 (Westinghouse, 1976)

Flow Name	Air Feed	N_2 Rejection	Power	O_2	Power	Coal Feed	Power	Ash Reject	Exhaust	O_2	O_2	Process Gas	Seed + Ash	Solids + Gas	Warmed Gas
Flow Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mass Rate, kg/s	73.99	56.75		17.24		21.72		2.09	7.18	14.2	3.04	43.5	36.55	80.05	36.3
Temperature, °K	300	300		300		300		1144	370	669	669	1144	350	960	760
Pressure, kPa	101	101		101		101		1520	101	1722	1722	1520	101	1520	1418
Power, kW			16136		1483		331.65		0.7066						
N_2, Mole Fraction	0.79	1.0		0					0	0	0	0		0	0
H_2	0	0		0					0	0	0	0.2788		0.2788	0.2167
CO	0	0		0					0.1632	0	0	0.3764		0.3764	0.2927
CO_2	0	0		0					0.1048	0	0	0.1464		0.1464	0.3921
H_2O	0	0		0					0	0	0	0.1324		0.1324	0.0128
H_2S	0	0		0					0	0	0	0 .011		0 .011	0
CH_4	0	0		0					0	0	0	0.0551		0.0551	0.0856
SO_2	0	0		0					0.0254	0	0	0		0	0
O_2	0.21	0		1.0					0	1.0	1.0	0		0	0
S, kg/s													0	0	
K_2SO_4													32.71	32.71	
K_2CO_3													0	0	
Ash								2.09					3.84	3.84	
Molecular Weight (Gas)	28.6	28							29.66	32	32	21.3		21.3	27.5

Table 3.2-2 Flow Chart for Seed Regeneration System for Westinghouse ECAS Base Case 2 (cont'd)

Flow Name	Steam	Process Gas	Cold Gas	Expanded Gas	Cool Process Gas	Cool Process Gas	Power	Power	Cool Water Make	Evap. Water	Sulfur + Water	K_2CO_3 K_2SO_4	Ash + Seed	Hot Gas to MHD	Steam Water
Flow Number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Mass Rate, kg/s	11.89	80.05	36.3	36.3	80.05	49.39			8.6	8.6	16.13	22.61	8.05	35.2	11.89
Temperature, °K	478	1040	332	598	541	541			300	373	420	541	541	899	478
Pressure, kPa	1722	1499	1428	607	1469	1444			101	101	1418	1418	1418	607	1722
Power, kW							9.2	221							
N_2, Mole Fraction	0	0	0	0	0	0			0	0	0			0	0
H_2	0	0.1522	0.2167	0.2167	0.1522	0.1522			0	0	0			0.2167	0
CO	0	0.2055	0.2927	0.2927	0.2055	0.2055			0	0	0			0.2927	0
CO_2	0	0.2753	0.3921	0.3921	0.2753	0.2753			0	0	0			0.3921	0
H_2O	1.0	0.2078	0.0128	0.0128	0.2078	0.2078			1.0	1.0	1.0			0.0128	1.0
H_2S	0	0.0990	0	0	0.0990	0.0990			0	0	0			0	0
CH_4	0	0.0601	0.0856	0.0856	0.0601	0.0601			0	0	0			0.0856	0
SO_2	0	0	0	0	0	0			0	0	0			0	0
O_2	0	0	0	0	0	0			0	0	0			0	0
S, kg/s		0									6.01	0	0		
K_2SO_4		4.28									0	3.61	0.673		
K_2CO_3		22.54									0	19.0	3.54		
Ash		3.84									0	0	3.84		
Molecular Weight (Gas)	18	26.3	27.5	27.5	26.3	26.3			18	18	18			27.5	18

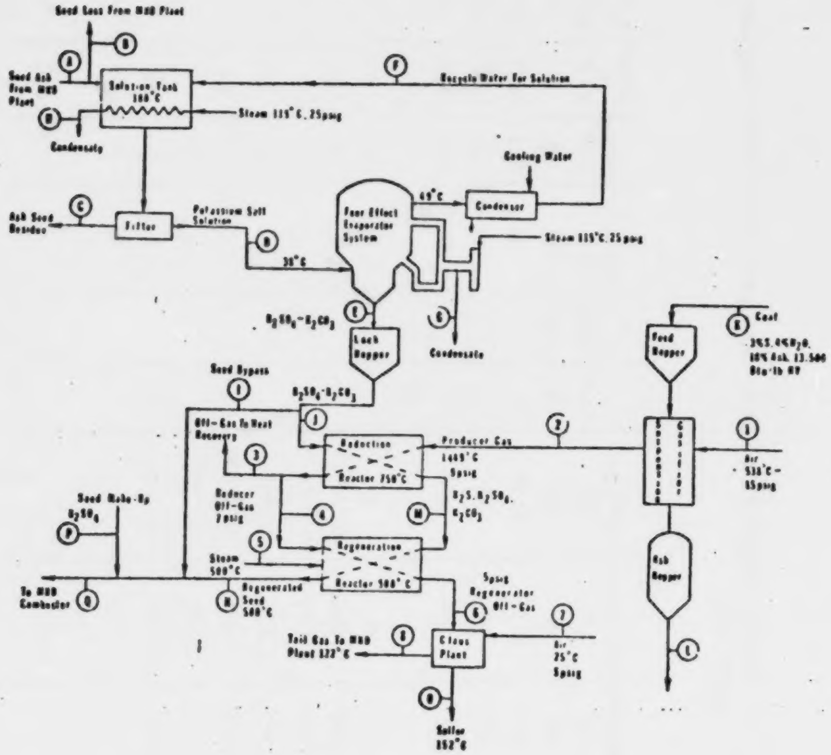

Seed Loss From MHD Plant
A
B
Seed Ash From MHD Plant
Solution Tank 100°C
Steam 115°C, 25psig
D
Condensate
F
Recycle Water For Solution
Cooling Water
Condenser
49°C
Four Effect Evaporator System
Steam 115°C, 25psig
C
Ash Seed Residue
Filter
Potassium Salt Solution
D
38°C
E
$K_2SO_4-K_2CO_3$
Lock Hopper
G
Condensate
Seed Bypass
I
$K_2SO_4-K_2CO_3$
J
Off-Gas To Heat Recovery
3
Reduction Reactor 750°C
Producer Gas
2
1469°C
5psig
Reducer Off-Gas 7psig
4
M
K_2S, K_2SO_4, K_2CO_3
Seed Make-Up
K_2SO_4
P
5
Steam 500°C
Regeneration Reactor 500°C
To MHD Combustor
Q
N
Regenerated Seed 500°C
5psig
Regenerator Off-Gas
6
7
Air 25°C 5psig
8
Tail Gas To MHD Plant 122°C
Claus Plant
0
Sulfur 152°C
K
Coal
3%S, 4%H_2O, 10% Ash, 13,500 Btu/lb HV
Feed Hopper
Gasifier
1
Air 538°C 15psig
Ash Hopper
L

Figure 3.2-12 Desulfurization Scheme for Combined Cycle MHD Power Plant (Bergman, et al., 1977)

Table 3.2-3 Solid and Liquid Streams - Material Balance for Base Case MHD Processing Scheme (Bergman, et al., 1977)

Solid or Liquid Streams

Flow Stream*	Coal**	Ash***	K_2SO_4 (lb/hr)	Sulfur	K_2S	K_2CO_3	H_2O	Enthalpy**** H (Btu/hr) $x10^{-6}$
A		4750	82100			4700		
B			820			50		
C		4700	810			50		
D		50	80460			4600	345080	
E		50	80460			4600		
F							345080	
G							78500	
H							33500	
I		10	12070			700		
J		40	68390			3900		-257.32
K	25370						1015	-29.76
L	1270	2280						-11.19
M		300	1370		42300	3910		-68.27
N		300	1370		1270	55470		-192.90
O				11600				0.87
P			1750					
Q		310	15190		1270	55470		

---

*See Figure 3.2-12

**Coal Analysis (4.95% H, 76.1% C, 1.0% N, 4.95% O, 3.0% S, 10.0% Ash, 4 Kg H_2O/100 Kg dry coal)

***Ash Analysis (28.0% Al_2O_3, 4.4% CaO, 15.0% Fe_2O_3, 1.6% K_2O, 1.1 % MgO, 0.8% Na_2O, 0.5% P_2O_5, 46.5% SiO_2, 1.3% TiO_2)

****At 298 K and 1 atm the enthalpy of all elements in that physical state is 0.

Table 3.2-4 Gaseous Streams - Material Balance for Base Case MHD Seed Processing Scheme (Bergman, et al., 1977)

Flow Stream* No	Flow Stream* Name	Mole % Ar	Mole % CO_2	Mole % CO	Mole % H_2	Mole % H_2O	Mole % H_2S	Mole % N_2	Mole % O_2	Mole % X	Volumetric Flow Rate acfh** X 10^{-6}	Enthalpy H*** X 10^{-6} Btu/hr
1.	Gasifier Air	0.92	0.03	-	-	1.26	-	77.10	20.69	-	1.45	21.91
2.	Producer Gas	0.70	3.06	24.86	8.80	3.67	0.29	58.64	-	0.08	1.92	-5.68
3.	Reducer Off-gas to heat recovery	0.70	24.25	3.67	1.31	11.16	0.29	58.54	-	0.08	1.25	-153.33
4.	Reducer Off-gas to regeneration	0.70	24.25	3.67	1.31	11.16	0.29	58.54	-	0.08	0.66	-80.60
5.	Steam	-	-	-	-	100.00	-	-	-	-	0.087	-23.32
6.	Regenerator Off-gas	0.75	4.34	3.95	1.40	4.34	22.01	63.12	-	0.09	0.62	-16.29
7.	Claus Plant Air	0.92	0.03	-	-	1.26	-	77.10	20.69	-	0.40	-1.48
8.	Claus Plant Tail Gas	0.64	5.46	-	-	18.23	.35	74.95	-	0.40	0.955	-65.57

* See Figure 3.2-12

** The molar gas volume is taken to be 359 ft^3 at 273 K and 1 atm.

*** At 298 K and 1 atm the enthalpy of all elements in that physical is 0.

Table 3.2-5 Energy Requirements for Seed Desulfurization in Base Case (Bergman, et al., 1977)

Coal Input (MWt)	98.2
Thermal Input (MWt)	
Air preheat	(6.92)
Steam for regeneration reaction	(0.51)
Total	(7.43)
Thermal Output (MWt)	
Gasifier steam	2.63
Reductor steam	11.79
Regenerator steam	11.44
Claus plant steam	13.77
Reductor gas, sensible heat, and heating value	15.87
Solids sensible heat	3.59
	59.09
Net heat recovered (MWt)	51.60
Electricity produced (40% efficiency, MWe)	20.64
Electrical input for auxiliaries (compressors, pumps, etc., MWe)*	(0.32)
Credit for carbonate production (MWe)	3.00
Net electricity production (MWe)	23.32

Effect on Efficiency

$$\frac{1000 + 23.32}{2000 + 98.2} = \frac{1023.3}{2098.2} = 48.77$$

Loss of Efficiency 50.00 - 48.80 = 1.23 points

---

*Includes seed leaching system energy consumption and assumes steam drives for pumps and gas compressors above 50 HP.

3.3 Energy Efficiency Evaluations

Table 3.3-1 shows the wide spread of estimates of OCMHD efficiencies. Of course some of this variation is due to lack of data and some is due to differences in designs. The energy losses at the points in several specific designs can be computed from the schmeatics in the previous section. This section begins with some general energy loss information and proceeds to the specific energy effects of changes in various design and operating parameters.

In comparison with other advanced energy cycles the Phase I ECAS studies shown how OCMHD's appear now to be competitive, Figures 3.3-1 and 3.3-2. With the axes reversed Figure 3.3-3 shows a slightly different set of results directly from the Westinghouse ECAS report. In the detailed ECAS Phase II studies the energy balance is shown in the flow chart in Figure 3.3-4. Table 3.3-2 displays a slightly more explicit breakdown of combustion losses; Table 3.3-3 shows additional detail on energy use of auxiliary components, and Table 3.3-4 shows a similar loss breakdown for the "reference" commercial facility of the future.

The best way to determine the energy efficiency changes due to particular parameter variations is currently through parametric investigations in the analytic system models. Some of these studies have been done as part of ECAS Phase I, Table 3.3-5. Unfortunately there were not enough of these parameteric studies to allow for a unique solution for the effects of various parametric changes. Statistically stated there are not enough values to ensure that predictive formulae would not capitalize on chance effects in the observed data. There have been some

TABLE 3.3-1

PROJECTED OVERALL OCMHD ENERGY EFFICIENCIES

Reference	Estimate
(Pomeroy, et al., 1978)	48.3% - 49.2%
(Cutting, et al., 1977)	46% - 46.9%
(NASA, 1977)	48.3% - 48.7%
(Penny, Bourgeois, Cain, 1977)	55% - 60%
(Bergman, Bienstock, 1976)	45.6% - 50.14%
(Jackson, et al., 1976)	47%
(NASA, 1976)	46% - 54% low Btu Westinghouse data
(NASA, 1976)	loss of 3% for seed reprocessing associated with high-sulfur coal
(Seikel, Harris, 1976)	41% - 53% (GE Co.)
(Seikel, Harris, 1976)	42% - 50% (WE Co.)
(Seikel, Harris, 1976)	48.3% (GE Co.)
(Westinghouse, 1976)	44% - 49% direct air preheat
(Westinghouse, 1976)	44% - 54%
(General Electric, 1975)	44% - 55%
(General Electric, 1975)	40% - 46% with solvent refined coal
(Pepper, Yu, 1975)	52% thermal
(Powell, Ulmer, 1974)	50% - 55%
(Feldmann, Simons, Bienstock, 1970)	50.8% - 51.9% thermal efficiency
(Hals, Jackson, 1969)	50% - 60%

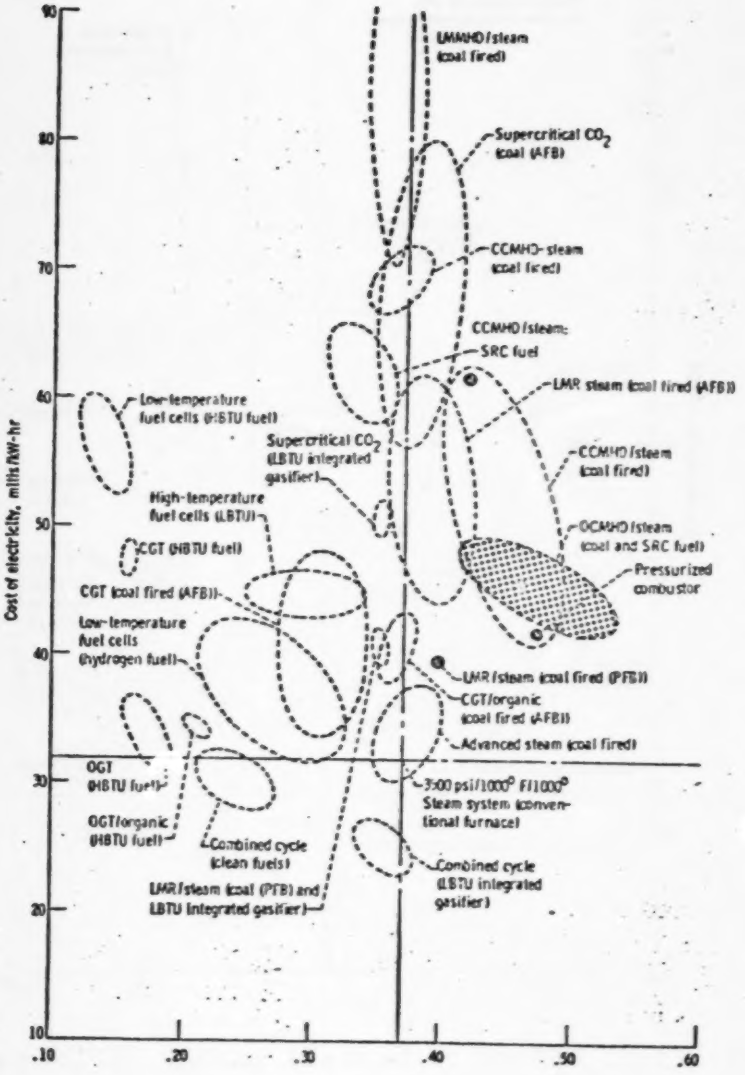


Figure 3.3-1 Effect of Overall Energy Efficiency on Cost of Electricity in General Electric Results with Shaded Area OCMHD (Seikel, Harris, 1976)

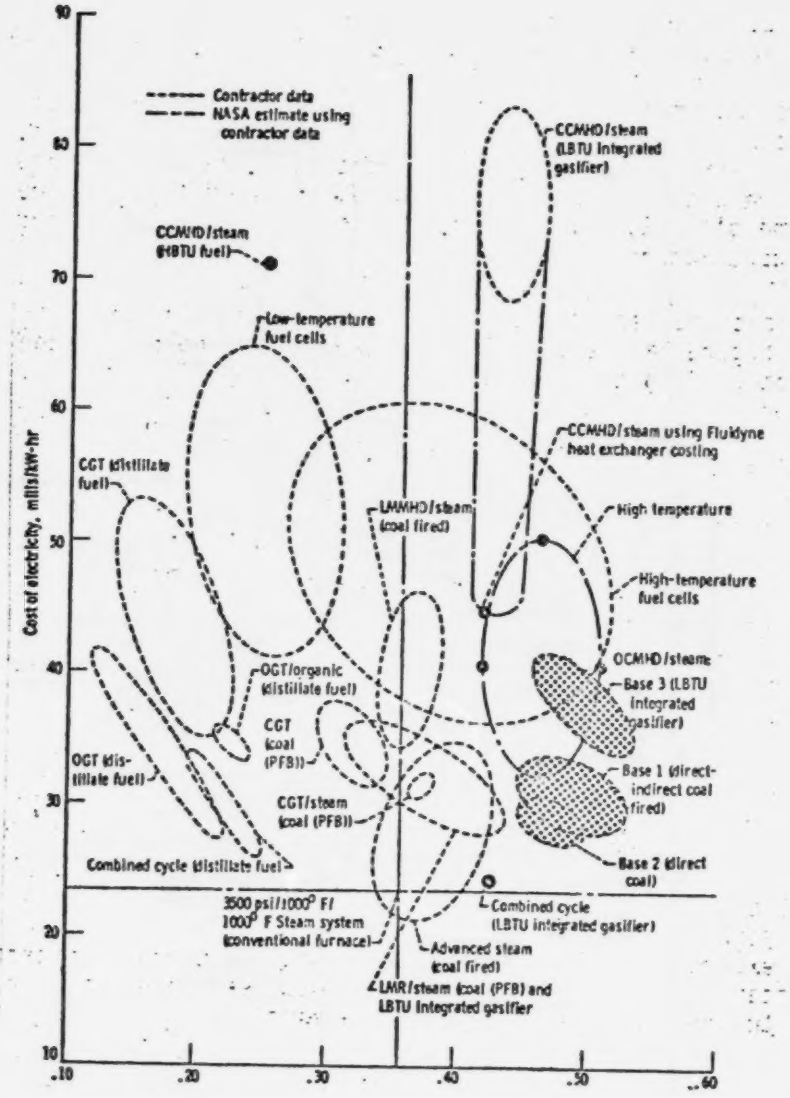
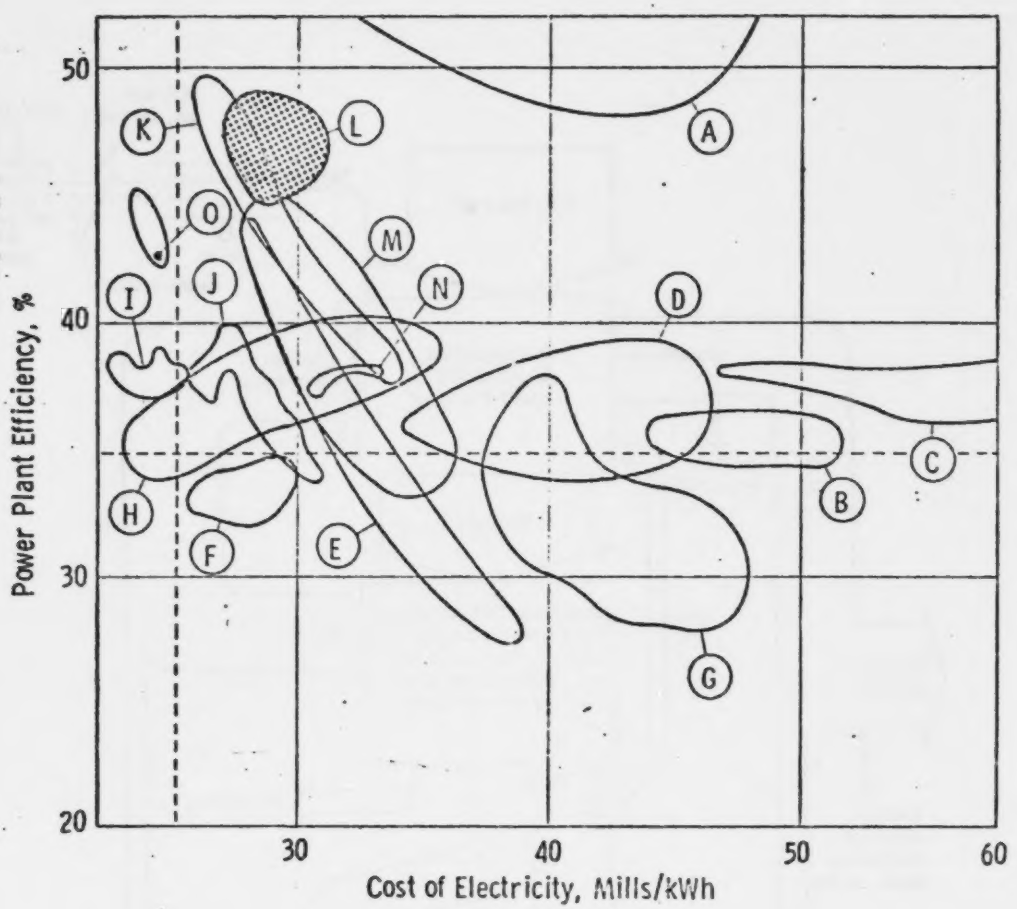


Figure 3.3-2 Effect of Overall Energy Efficiency on Cost of Electricity in Westinghouse Results with Shaded Areas OCMHD (Seikel,Harris, 1976)



A-Fuel Cell Steam Bottoming
  1-Molten-Carbonate
  2-Solid Electrolyte
B-Fuel Cell (Phosphoric Acid)
C-Alkaline Fuel Cells
D-Liquid Metal MHD
E-Recuperated-Open-Cycle Gas Turbine
F-Closed Recuperated Gas Turbine (Coal)
G-Recuperated-Closed-Cycle Gas Turbine
H-Steam (Atmospheric Boiler)
I-Steam (Pressurized Fluidized Bed Boiler)
J-Steam (Pressurized Boiler)
K-Distillate-Burning Combined-Gas Turbine
L-Open-Cycle MHD
M-Metal Vapor Rankine Topping Cycle
N-Combined-Closed-Cycle Gas-Steam Turbine
O-Coal Burning Combined-Cycle-Gas Steam Turbine

Figure 3.3-3 Advanced Energy-Conversion Systems - Range of Results with Shaded Area OCMHD (Beecher, et al. 1976)

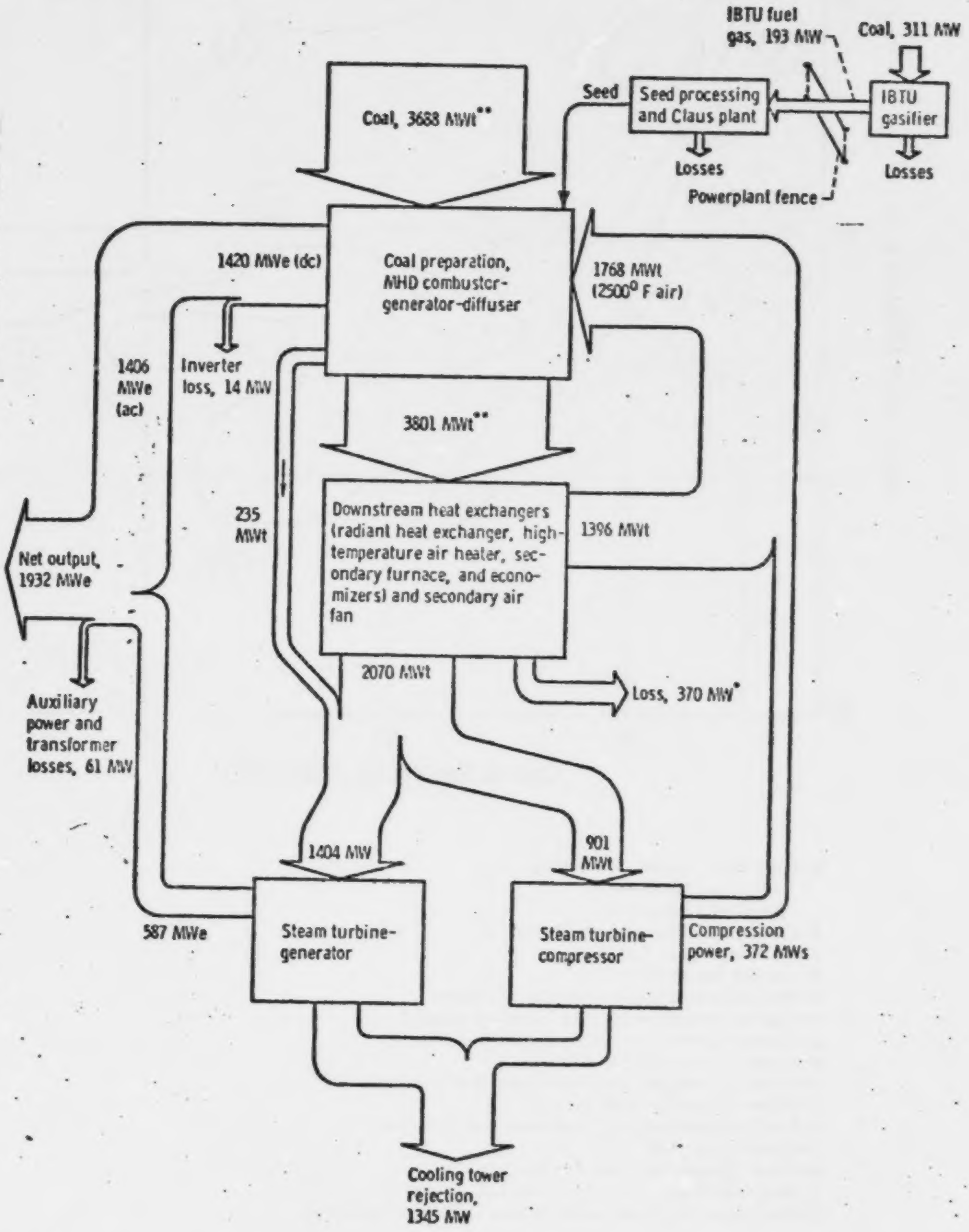

IBTU fuel gas, 193 MW
Coal, 311 MW
Seed
Seed processing and Claus plant
IBTU gasifier
Losses
Losses
Powerplant fence
Coal, 3688 MWt**
1420 MWe (dc)
Coal preparation, MHD combustor-generator-diffuser
1768 MWt (2500° F air)
1406 MWe (ac)
Inverter loss, 14 MW
3801 MWt**
235 MWt
Downstream heat exchangers (radiant heat exchanger, high-temperature air heater, secondary furnace, and economizers) and secondary air fan
1396 MWt
Net output, 1932 MWe
2070 MWt
Loss, 370 MW*
Auxiliary power and transformer losses, 61 MW
1404 MW
901 MWt
587 MWe
Steam turbine-generator
Steam turbine-compressor
Compression power, 372 MWs
Cooling tower rejection, 1345 MW

Figure 3.3-4 Simplified Energy Flow Diagram for Phase 2 Conceptual Powerplant - Coal/Open Cycle MHD/ Steam System (NASA, 1977)

Table 3.3-2 Energy Balance for Combustion Flow
(Harris, Shah, 1976)

Energy Outputs			
*MHD power output		1420	
*Combustor/channel/diffuser cooling		235	
*Radiant furnace heat transfer		983	
*HTAH heat transfer		857	
*Secondary furnace heat transfer		1298	
*(Economizers		328	
(Coal dryers		8	
Leaving losses		370	
Coal ash (sensible + latent)	22		
K_2SO_4 (sensible + latent)	10		
Combustion gas (sensible)	183		
Combustion gas (latent)	155		
Energy Inputs Other Than Combustion			
Air heating (857 + 539)		1396	
Air compressor power		372	
Coal heating in mills, dryers		8	
Net Energy Output			3723 MWt
Combustion Energy Input			3750 MWt
Fuel HHV @ 10.788 Btu/lb	3688		
Correction for $SO_x \rightarrow K_2SO_4(G)$	17		
Condensation and solidification of K_2SO_4	45		
Excess Energy Input			27 MWt

*Values specified by system advocate

Table 3.3-3 Auxiliary Power Requirements and Electrical Losses for ECAS Open Cycle MHD (Harris, Shah, 1976)

ITEM	ASSUMPTIONS	NO. OF UNITS	MW_e EACH	TOTAL MW_e
PUMPS				
CONDENSATE	A/E ESTIMATE	4		1.46
CIRCULATING WATER	PROPORTIONAL TO COOLING TOWER HEAT LOAD	3		4.61
AIR BLOWER	$\eta = 80\%$	1		1.00
COOLING TOWERS	PROPORTIONAL TO HEAT LOAD	25		2.15
COAL HANDLING	¾ OF EQUIPMENT RATING			2.25
COAL PROCESSING	EQUIPMENT RATING			14.00
MHD COMPONENTS	0.75% MHD POWER			10.50
TURBINE AUXILIARIES	0.75% STEAM POWER			6.90
"HOTEL" LOAD	A/E ESTIMATE			6.37
MAKEUP WATER TREATMENT	A/E ESTIMATE			.75
INTAKE STRUCTURE	A/E ESTIMATE			.75
INVERTER LOSSES	1% MHD D-C OUTPUT			14.2
TRANSFORMER LOSSES	0.5% 60 Hz GENERATION			9.96
				74.9

Table 3.3-4 OCMHD System Energy Balance for Eventual Commercial OCMHD (Jackson, et al., 1976)

	KW	KW
GENERATORS		
MHD	634,000	
Steam Turbine	370,408	
Subtotal Generators		1,004,408
MOTORS (CALCULATED)		
Secondary Air Fan	484	
Circulating Water Pump	4,907	
Condensate Pump	1,230	
Boiler Feed Booster Pump	766	
Induced Draft Fan	7,556	
Subtotal Motors		-14,943
PLANT AUXILIARIES (ESTIMATED)		
Main Steam Turbine	295	
Fuel Handling	6,307	
Ash Handling	1,636	
Service Water System	293	
MHD Transformer	12,683	
Steam Turbine Transformer	5,548	
Seed Handling	10,000	
Inverter	6,311	
Cleanup System	13,671	
Magnet	1,000	
Miscellaneous	1,936	
Subtotal Auxiliaries		-59,680
TOTAL PLANT OUTPUT (NET)		929,785
COAL BURNER		
LB/HR	616,009	
HHV	11,081	
BTU/SEC	1,896,111	
KW_{th}	2,000,000	
STATION HEAT RATE (BTU/KWH) (BASED ON HHV)		7341
STATION EFFICIENCY (%)		46.50

Table 3.3-5 Parametric Variations for General Electric ECAS Task I Study Open Cycle MHD (Corman, et al., 1976)

Parameters	Common Elements: Direct Coal Combustion, Avco Combustors, and Refractory S														
	Case 1*	2	3	4	5	6	7	8**	9	10	11	12	13	14	15
Power Output (MWe)	1895	1180	599	1870	1867	1888	1888	1426	1991	1994	2017	2073	1738	1929	1799
Combustion															
Coal	Ill. #6 →			Mont	N. D.	Ill. #6 →									
Oxidizer	Air →								Air/O_2	Air →					
Combustor slag rejection (percent)	90 →					80	0	90 →							
Preheater															
Firing	Direct →									Indirect	Direct →				
Oxidizer temperature (°F)	2500 →								1500	3101 →			2000	2500 →	
MHD Generator															
Type	Faraday →														
Inlet pressure (atm)	9	8.9	8.7	7	6.5	9 →		7	10.2	11.5	13.0	16	6	8.7	9 →
Average magnetic field (T)	5 →											6	5 →		
Potassium seed (percent)	1.0 →														
Electrical load parameter	0.8 →													0.85	0.7
Heat Exchangers															
Gas (Δp/p)	0.15 →														
Air (Δp/p)	0.10 →														
Steam Bottoming Cycle															
Turbine inlet temperature (°F)	1000/1000 →														
Turbine inlet pressure (psi)	3500 →														
Maximum feedwater temperature (°F)	232 →														
Air Bottoming Cycle															
Turbine inlet temperature (°F)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pressure ratio	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Heat Rejection (in. Hg)	WCT 1.5 →														
Actual Powerplant Output (MWe)	1895	1180	599	1870	1867	1888	1888	1426	1991	1994	2017	2073	1738	1929	1799
Thermodynamic Efficiency (percent)	52.8	52.0	52.3	49.6	48.4	52.7	52.7	51.6	50.0	55.5	56.1	57.7	48.6	53.7	50.2
Powerplant Efficiency (percent)	49.2	48.5	48.7	47.9	46.5	49.1	49.1	47.2	46.9	51.8	52.4	53.9	45.1	50.1	46.8
Overall Energy Efficiency (percent)	48.3	47.6	47.8	47.8	46.3	48.1	48.1	46.1	46.1	50.8	51.4	52.8	44.3	49.2	45.9
Coal Consumption (lb/kWh)	0.65	0.67	0.66	0.80	1.07	0.66	0.66	0.69	0.69	0.62	0.62	0.60	0.71	0.64	0.69
Plant Capital Cost ($ million)	2090	1239	715	2060	2107	2092	2091	2018	2016	2164	2152	2173	2052	2116	2059
Plant Capital Cost ($/kWe)	1102	1049	1193	1101	1128	1108	1107	1415	1012	1085	1067	1048	1181	1096	1144
Cost of Electricity, Capacity Factor = 0.65															
Capital (mills/kWh)	34.9	33.2	37.7	34.8	35.7	35.0	35.0	44.7	32.0	34.3	33.7	33.1	37.3	34.7	36.2
Fuel (mills/kWh)	6.2	6.3	6.3	6.1	6.3	6.3	6.3	6.6	8.8	5.9	5.9	5.7	6.8	6.1	6.6
Maintenance and operating (mills/kWh)	2.8	2.9	3.2	2.9	2.9	2.8	2.8	3.6	2.3	2.9	2.7	2.6	3.0	2.7	2.9
Total (mills/kWh)	43.9	42.4	47.3	43.8	44.9	44.1	44.1	55.0	43.1	43.1	42.3	41.4	47.1	43.5	45.6
Sensitivity															
Capacity factor = 0.50 (total mills/kWh)	55.1	53.2	59.6	55.2	56.5	55.4	55.4	69.5	53.6	54.2	53.2	52.1	59.2	54.7	57.4
Capacity factor = 0.80 (total mills/kWh)	36.8	35.6	39.6	36.8	37.7	37.0	37.0	45.9	36.6	36.1	35.4	34.7	39.6	36.5	38.3
Capital Δ = 20 percent (Δ mills/kWh)	7.0	6.6	7.5	7.0	7.1	7.0	7.0	8.9	6.4	6.9	6.7	6.6	7.5	6.9	7.2
Fuel Δ = 20 percent (Δ mills/kWh)	1.2	1.3	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.1	1.4	1.2	1.3
Estimated Time for Construction (years)	7	6	6	7	7	7	7	7	7	7	7	7	7	7	7
Estimated Date of 1st Commercial Service (year)	1997	1997	1997	1997	1997	1997	1997	1997	1993	1993	1999	1999	1995	1997	1997

*Base case 1.
**Base case 1 configuration, reduced power output.
† Base case 2.

DCT = Dry cooling tower
HT = High temperature
Ill. = Illinois

Mont = Montana
N. D. = North Dakota
WCT = Wet cooling tower

Table 3.3-5 (cont'd)

Parameters	orage HT Air Preheater								Common Elements: SRC Fuel, Avco Combustor, and Refractory Storage HT Air Preheater						
	16	17	18	19	20	21	22	23	24 *	25	26	27	28	29	30
Power Output (MWe)	1701	1895	1895	1883	1901	1870	1999	1889	1932	1754	2005	1931	1937	1942	1919
Combustion															
Coal	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Oxidizer	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Combustor slag rejection (percent)	→	→	→	→	→	→	→	→	0 →	→	→	→	→	→	→
Preheater															
Firing	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Oxidizer temperature (^0F)	→	→	→	→	→	→	→	→	3100	2500	3600	3100 →	→	→	→
MHD Generator															
Type	→	→	→	Diagonal Faraday		→	→	→	Faraday →	→	→	→	→	→	→
Inlet pressure (atm)	→	→	→	→	→	→	→	→	15	9	20	15 →	→	→	→
Average magnetic field (T)	→	6	7	5 →	→	→	→	→	6 →	→	→	5	7	6 →	→
Potassium seed (percent)	→	→	→	→	0.5	1.5	1.0 →	→	→	→	→	→	→	0.5	1.5
Electrical load parameter	0.6	0.8 →	→	→	→	→	→	→	→	→	→	→	→	→	→
Heat Exchangers															
Gas (Δp/p)*	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Air (Δp/p)	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Steam Bottoming Cycle															
Turbine inlet temperature (^0F)	→	→	→	→	→	→	--	1000/100 →	→	→	→	→	→	→	→
Turbine inlet pressure (psi)	→	→	→	→	→	→	--	3500 →	→	→	→	→	→	→	→
Maximum feedwater temperature (^0F)	→	→	→	→	→	→	--	232 →	→	→	→	→	→	→	→
Air Bottoming Cycle															
Turbine inlet temperature (^0F)	--	--	--	--	--	--	2400	--	--	--	--	--	--	--	--
Pressure ratio	--	--	--	--	--	--	10	--	--	--	--	--	--	--	--
Heat Rejection (in. Hg)	→	→	→	→	→	→	→	DCT 1.8	WCT 1.5 →	→	→	→	→	→	→
Actual Powerplant Output (MWe)	1701	1895	1895	1883	1901	1870	1999	1889	1932	1754	2005	1931	1937	1942	1919
Thermodynamic Efficiency (percent)	47.6	52.8	52.8	52.5	53.0	52.1	55.5	52.8	58.2	53.0	60.4	58.2	58.4	58.6	57.9
Powerplant Efficiency (percent)	44.2	49.2	49.2	48.9	50.4	47.6	51.9	49.1	56.8	51.6	58.9	56.8	56.9	57.1	56.4
Overall Energy Efficiency (percent)	43.4	48.3	48.3	48.0	49.9	46.3	50.9	48.1	44.3	40.2	46.0	44.3	44.4	44.5	44.0
Coal Consumption (lb/kWh)	0.73	0.65	0.65	0.66	0.63	0.68	0.62	0.66	0.71	0.79	0.69	0.71	0.71	0.71	0.72
Plant Capital Cost ($ million)	2036	2028	2024	2089	2105	2089	2304	2153	1866	1783	1883	1870	1852	1873	1859
Plant Capital Cost ($/kWe)	1197	1069	1067	1109	1107	1117	1152	1140	965	1016	939	968	956	964	968
Cost of Electricity, Capacity Factor = 0.65															
Capital (mills/kWh)	37.8	33.8	33.8	35.1	35.0	35.3	36.4	36.0	30.5	32.1	29.7	30.6	30.2	30.5	30.6
Fuel (mills/kWh)	7.0	6.2	6.2	6.3	5.9	6.6	5.9	6.3	10.8	11.9	10.4	10.8	10.8	10.8	10.9
Maintenance and operating (mills/kWh)	3.1	2.8	2.8	2.8	2.7	2.8	3.2	2.8	2.8	3.0	3.0	2.8	2.8	2.8	2.8
Total (mills/kWh)	47.9	42.8	42.7	44.1	43.7	44.7	45.6	45.1	44.1	47.0	43.1	44.2	43.8	44.0	44.3
Sensitivity															
Capacity factor = 0.50 (total mills/kWh)	60.2	53.8	53.7	55.5	55.0	56.1	57.5	56.7	54.1	57.6	52.9	54.3	53.7	54.0	54.6
Capacity factor = 0.80 (total mills/kWh)	40.2	36.0	35.9	37.0	36.6	37.6	38.1	37.8	37.9	40.4	37.0	38.0	37.6	37.8	38.1
Capital Δ = 20 percent (Δ mills/kWh)	7.6	6.8	6.8	7.0	7.0	7.1	7.3	7.2	6.1	6.4	5.9	6.1	6.0	6.1	6.1
Fuel Δ = 20 percent (Δ mills/kWh)	1.4	1.2	1.2	1.3	1.2	1.3	1.2	1.3	2.2	2.4	2.1	2.2	2.2	2.2	2.2
Estimated Time for Construction (years)	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Estimated Date of 1st Commercial Service (year)	1997	1997	1997	1997	1997	1997	1999	1997	1999	1995	2003	1999	1999	1999	1999

additional investigations of efficiency changes due to variations in one parameter, the moisture content of the coal, Tables 3.3-6, 3.3-7 and 3.3-8. Attempts to model the effects of parameter changes have been made for sulfur content of coal, Figure 3.3-5, and for channel wall temperature and pressures, Figures 3.3-6 and 3.3-7.

Some crude initial models of OCMHD efficiencies are shown in Figures 3.3-8 and 3.3-9.

Table 3.3-6 Energy Balance for 2000 MWt MHD Power Plant Operating on Eastern and Western Coal with Thermal Drying (Bergman, Bienstock, 1976)

	Pittsburgh Seam	Rosebud Seam		
Moisture Level (wt. H_2O)x100/(wt. dry coal)	2	2	10	27.4
Gross MHD Channel Power, MWe	634.54	601.12	581.96	532.15
Gross Steam Plant Power, MWe	583.31	593.50	592.80	595.25
Compressor Power, MWe	171.17	172.23	172.23	172.23
Plant Auxiliaries and Electrical Losses, MWe	43.82	43.60	43.19	42.32
Net Power, MWe	1002.86	978.79	959.34	912.85
Drying Energy, MWt [1]	0	93.0	66.1	0
Efficiency, %	50.14	46.74	46.43	45.64

[1] Drying energy is supplied by combustion of an auxillary fuel in the dryer.

Table 3.3-7 Energy Balance for 2000 MWt MHD Power Plant Operating on Eastern and Western Coal with Steam Drying (Bergman, Bienstock, 1976)

	Pittsburgh Seam	Rosebud Seam		
Moisture (wt H_2O) x 100/ (wt dry coal)	2	2	10	27.4
Gross MHD Channel Power, MWe	634.54	601.12	581.96	532.15
Gross Steam Plant Power, MWe	583.31	585.47	587.10	595.25
Compressor Power, MWe	171.17	172.23	172.23	172.23
Plant Auxiliaries and Electrical Losses, MWe	43.82	43.26	42.94	42.32
Net Power, MWe	1002.86	971.10	953.89	912.85
Drying Energy, [1] MWt	0	33.8	24.0	0
Efficiency, %	50.14	48.56	47.69	45.64

[1] Drying energy comes from waste steam deposited in steam bottoming plant from MHD topping cycle.

Table 3.3-8 Energy Efficiency Effects of Various Systems Parameters (Annen, Eustis, 1977)

	Illinois #6 Coal						Montana Rosebud Coal					
	Separate Flow Air Turbine		Separate Flow Gas Turbine		Single Flow Gas Turbine		Separate Flow Air Turbine		Separate Flow Gas Turbine		Single Flow Gas Turbine	
Air Preheat Temp.	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K
Net Power from MHD cycle (MHD PWR-compressor power), MW	636.7	544.5	599.8	513.8	707.9	599.6	648.3	554.7	628.8	541.9	734.0	619.1
Net Power from Air/Gas Turbine, MW	269.9	319.6	297.7	343.4			271.6	321.6	284.5	335.2		
Net Power from Bottoming Cycle, MW	130.2	143.6	134.1	142.8	327.8	383.0	119.2	133.3	116.8	128.8	313.5	368.7
Total Power, MW	1036.8	1007.7	1031.6	1000.0	1035.7	982.6	1039.1	1009.6	1030.1	1005.9	1047.5	987.8
Thermal Efficiency (based on lower heating value) %	51.8	50.4	51.6	50.0	51.8	49.1	52.0	50.5	51.5	50.3	52.4	49.4
Bottoming Cycle and Intercooler Heat Rejection (proportional to cooling water requirement) MW	384.4	424.0	400.6	424.9	540.1	631.3	352.0	391.3	366.3	397.7	516.7	607.7
MHD Mass Flow Rate kg/sec	763		665		806		772		692		826.6	
Air/Gas Turbine Mass Flow Rate kg/sec	1479	1751	830	1080			1488	1762	838	1111		
MHD Combustor Flame Temp. °K	2932	2841	2963	2870	2794	2689	2934	2843	2963	2871	2805	2700
MHD Duct Length	18.2	15.2	20.1	16.7	13.4	10.3	18.8	15.4	20.2	17.2	14.5	10.7

(Thermal Input = 2000 MW)

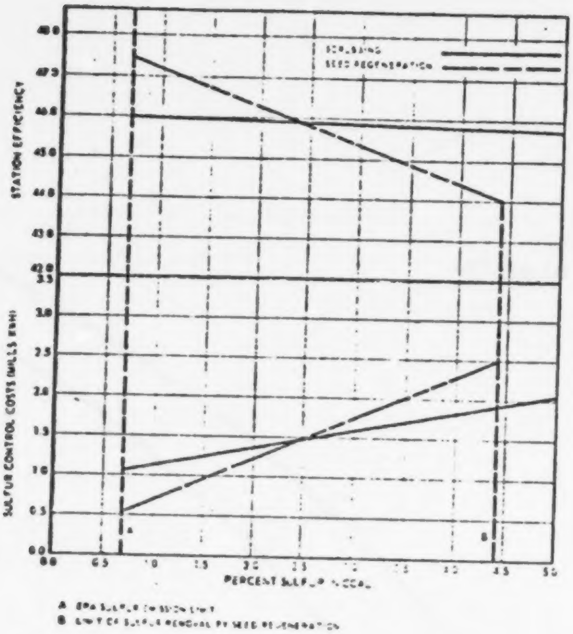


Figure 3.3-5 Baseline Plant Station Efficiency and Sulfur Control Costs vs. Coal Sulfur Content (Jackson, et al., 1976)

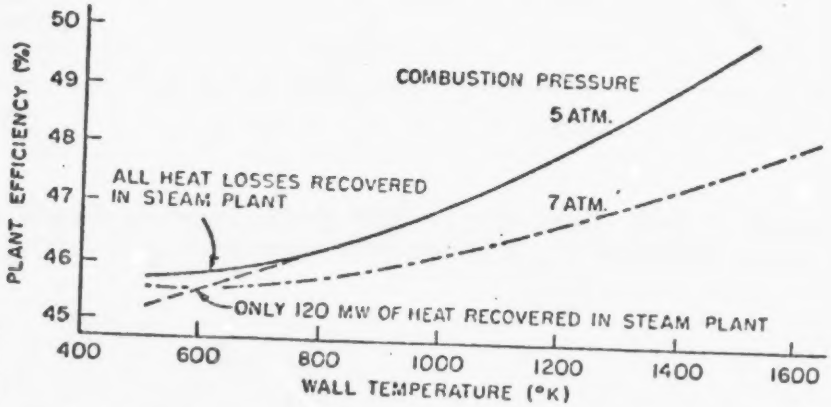


Figure 3.3-6 Effect of MHD Channel Wall Temperature and Associated Heat Losses on Cycle Efficiency for Two Different Combustion Pressures (REA, 1975)

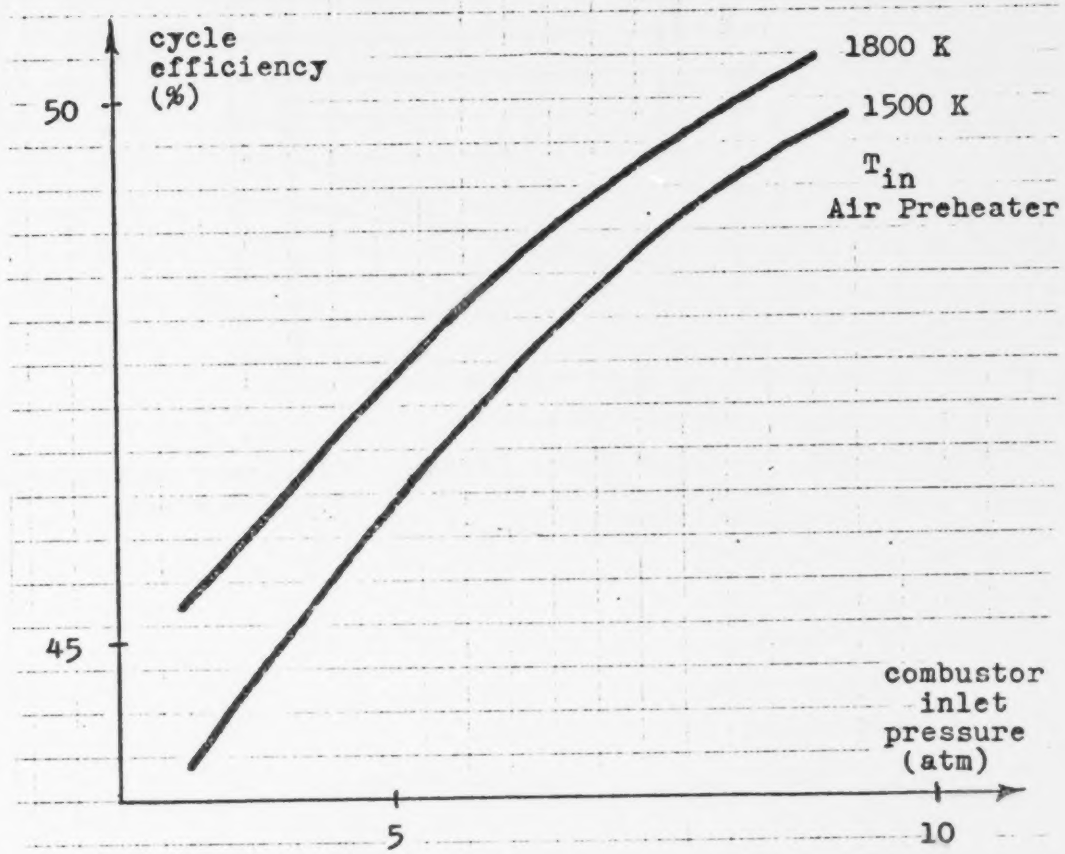


Figure 3.3-7 Open Cycle MHD Efficiency Variation with Changes in Combustor Pressure(Amend,1975)

Model of Overall Energy Efficiency of OCMHD:

$$
\begin{aligned}
E = {} & .415 - 1.392C + 3.977A - .00056R - .004F + .0229T - .0115G \\
& + 1.535P - 10.98M - 1.842S + 23.13L + 1.87B + .0122W \\
& + .00615W\,M - .00216W\,P - .00001W\,T + .218M\,P \\
& - .000836M\,T + .00057P\,T - 1.035(C-2.2)^2
\end{aligned}
$$

E = Overall energy efficiency of OCMHD design, in percent
C = Coal type: Ill #6=1, Montana= 2, N.D.=3, SRC=4
A = Combustion oxidizer: air=1, air/O2=2
R = Combustor slag rejection in percent
F = Preheater firing: direct=1, indirect=2
T = Temperature in °F of preheated air
G = Generator type: Faraday=1, diagonal Faraday=2
P = Generator inlet pressure in atmospheres
M = Average magnetic field strength in Teslas
S = Potassium seeding in percent
L = Electrical load parameter,as fraction
B = Bottom cycle type: steam=1, air=2
W = power output of OCMHD, in megawatts

Fit to 39 parametric designs with arithmetic standard deviation equal to 0.28%
Correlation of actual to predicted values is R^2=.985

Figure 3.3-8 Simplified model fit to the energy efficiency result from GE ECAS Task 1 (Corman, et al., 1976).

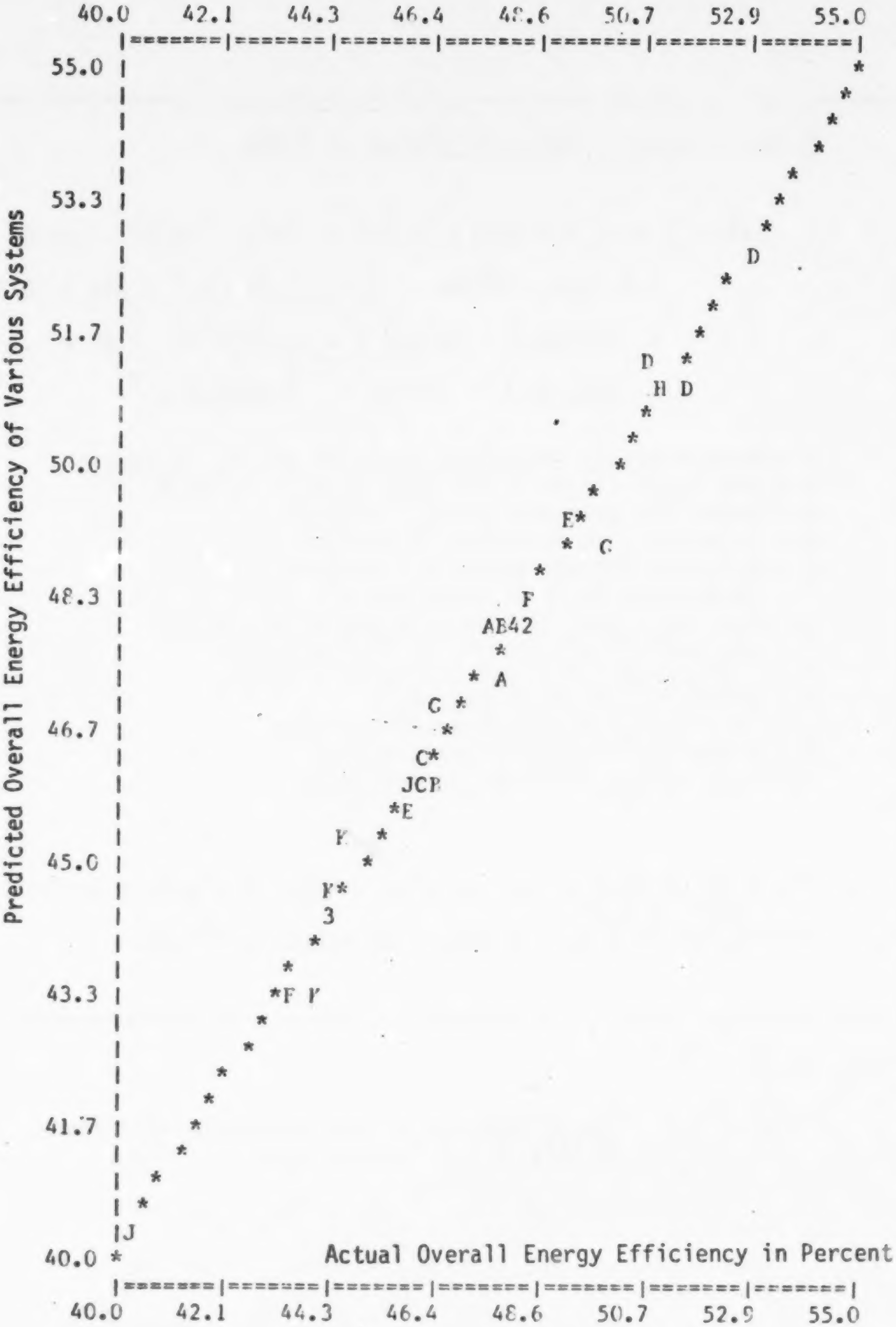


Figure 3.3-9 Scatterplot of predicted efficiencies versus those analytically derived in GE ECAS Task 1, different letters refer to different types of system configurations.

4. Environmental Assessment

The primary impetus for developing open cycle MHD power plants is the economic attractiveness. Some of this economic potential is due to the very high efficiencies of these cycles and part is due to the lack of need for scrubbers. Investigations to date indicate that there are other environmental gains possible, but data are still lacking on many key points. In particular only a few of the potential air pollution emissions have been studied whereas the list of possible pollutants from fossil-fuel facilities includes more than 602 inorganic pollutants and 491 organics. Liquid emissions are expected to be total suspended solids, oil, grease, copper, iron, other heavy metals, and thermal discharges (Penny, *et al.*, 1977). Solids will be dominated by furnace wastes, other collected solids, and sulfur. The following sections deal in more detail with the particular emissions that have been studied to date.

4.1 Air Emissions

When they come on line OCMHD power plants will have to meet either the EPA New Sources Performance Standards or updated (probably stricter) standards for air pollution from stationary coal-fired power plants, presented in Table 4.1-1. The following sections deal specifically with these emissions, and a summary of these and other environmental and economic data can be found in Appendix A.

4.1.1 Sulfur Oxides

Some projections of OCMHD sulfur oxide emissions are shown in Table 4.1.1-1. The ash holds about 2.4% of the sulfur, and high combustion efficiencies reduce sulfur emissions, see Figure 4.1.1-1,but the

TABLE 4.1-1

ENVIRONMENTAL EMISSION STANDARDS FOR SOLID-FUELED SOURCES

Pollutant	Standard (lb/MBtu)	Possible Future Standard (EPRI-predicted) (lb/MBtu)
SO_x	1.20 (as SO_2)	0.60 to 0.30 (as SO_2)
NO_x	0.70 (as NO_2)	0.40 to 0.13 (as NO_2)
Total Particulates	0.10	0.10 to 0.05
Fine Particulates (less than 3 microns)	none	0.10 to 0.02

TABLE 4.1.1.-1

ESTIMATES OF SULFUR OXIDE EMISSIONS FROM OCMHD

Reference	lb/10^6 Btu input	lb/kWh output
(General Electric, 1976) base case	1.2	.008
(General Electric, 1976) SRC	0.8	.0062
(Jackson, et al., 1976) reference	less than 1.2	-
(Shaw, Cain, 1977)	0.77 g/kWht	1.6 g/kWhe
(Penny, et al., 1977)	-	5 ppm
(Hals, Jackson, 1977)		
fertilizer recovery system	-	100 ppm
(Harris, Shah, 1976)	0.5	.0034
(REA, 1976)	0.045	-

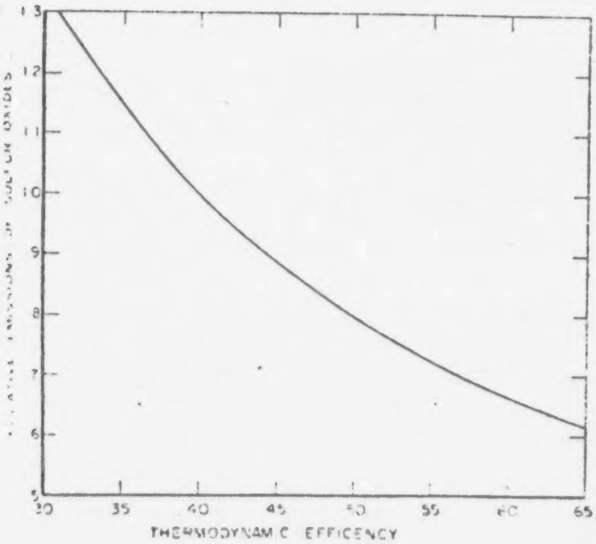


Figure 4.1.1-1 SO_2 Emissions as a Function of Power Plant Efficiency (Bienstock, et al., 1971)

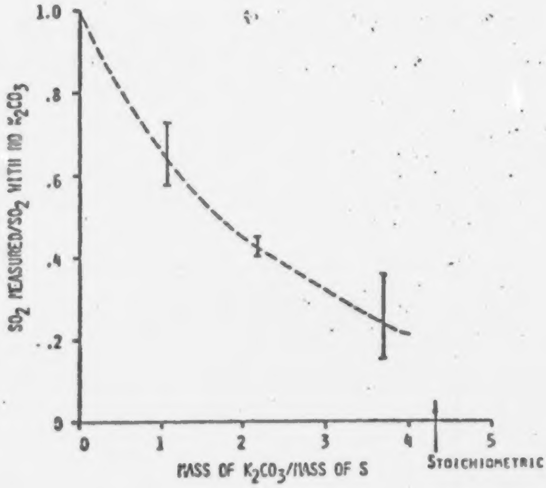


Figure 4.1.1-2 Sulfur Removal by Potassium Carbonate Addition (Dicks, et al., 1977)

overwhelmingly dominant influence on the level of these emissions is the amount of seed material used. As can be seen from Table 4.1.1-2 or from Figure 4.1.1-2 the concentration of SO_2 in the emissions can be lowered to almost any desired value, see Figure 4.1.1-3. This is a very impressive advantage of MHD cycles, however, there are fairly substantial economic and energy-efficiency penalties for high removal percentages. An interesting trade-off then presents itself requiring a choice among low-sulfur coal, beneficiated coal, high seeding levels, and post-combustion sulfur oxide removal. Expectations for commercial-sized facilities (Jackson, et al., 1976) show that the seed recovery method of sulfur oxide control is likely to be the most cost effective technique, 0.5% efficiency penalty versus 1.5% and 3.0% for flue gas desulfurization and coal cleaning (Jackson, et al., 1976), and 1.5% for nitrogen maximization (Cutting, et al., 1977).

Table 4.1.1-2 Removal of Sulfur Oxides in MHD Power Generation with K_2CO_3 as Seed (Bienstock, et al., 1971)

Wgt % of sulfur in coal: 2.2
105% of stoichiometric oxygen
$N_2/O_2 = 2$

Seed concentration				
g moles K_2CO_3 / kg coal	lb K_2CO_3 / 100 lb coal	SO_2 in combustion gas, ppm	SO_2 removal, %	Actual SO_2 removal / stoichiometric removal[a] × 100
0	0	2735	-	-
0.37	5	1608	41.2	~~78~~ 94
0.72	10	102	96.3	~~87~~ 95
0.90	12.5	35	98.7	~~73~~ 82
1.02		5	99.8	65

[a] Based on formation of K_2SO_4.

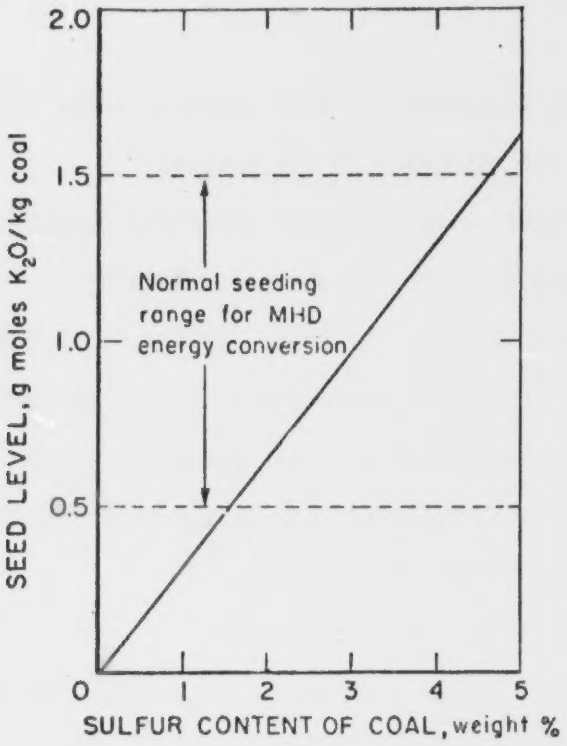


Figure 4.1.1-3 MHD Plasma Seeding Levels for Completely Eliminating Sulfur From Coal (Bienstock, et al., 1974)

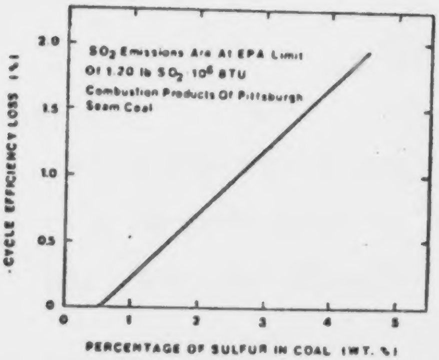


Figure 4.1.1-4 Effect of Sulfur Content on Cycle Efficiency Loss (Bergman, et al., 1977)

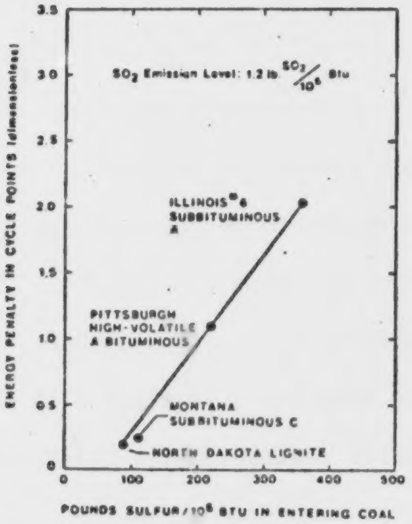


Figure 4.1.1-5 Energy Consumed in Seed Regeneration vs. Type of Coal Employed (Bergman, et al., 1977)

Once the seeding technique has been selected there are several factors that affect the economics of the process:

(1) the seed material used, almost certainly potassium carbonate, but possibly cesium carbonate or a mixture;

(2) the sulfur content of the coal, Figures 4.1.1-4 and 4.1.1.-5, and degree of control desired will affect the amount of potassium sulfate that must be regenerated, see Table 4.1.1-3;

(3) lesser control translates into lesser requirements for reducing gas and thus less equipment; and

(4) threshold standard, Figure 4.1.1-6.

From the initial sulfur in the coal to the sulfur that would come from a Claus plant, the principal reactions are:

$$S + O_2 = SO_2$$

$$2SO_2 + 2K_2CO_3 + O_2 = 2K_2SO_4 + 2CO_2$$

$$K_2SO_4 + 2(CO + H_2) = K_2S + 2(CO_2 + H_2O)$$

$$K_2S + CO_2 + H_2O = K_2CO_3 + H_2S$$

$$2H_2S + 3O_2 = 2SO_2 + 2H_2O$$

$$2H_2S + SO_2 = 3S + H_2O.$$

A previously mentioned alternative to the seeding procedure is the post-combustion removal option. In the particular design where NO is maximized to be drawn off as a fixed nitrogen source for fertilizers the nitrogen oxides convert the SO_2 to SO_3 which is easily removed as sulfuric acid (Hals, Jackson, 1969). Concentrations as low as 100 ppm are apparently possible with this operating configuration, described a little further in the following section.

Table 4.1.1-3 Required Percent of K_2SO_4 to Sulfur-free Potassium Compounds (Jackson, et al., 1976)

Coal	Wt. % Sulfur	Conversion %
Pennsylvania (Pittsburgh)	1.6	16
West. Kentucky	3.3	52
Illinois #6	3.3	57–71
Montana (Rosebud)	0.85	8 - 12

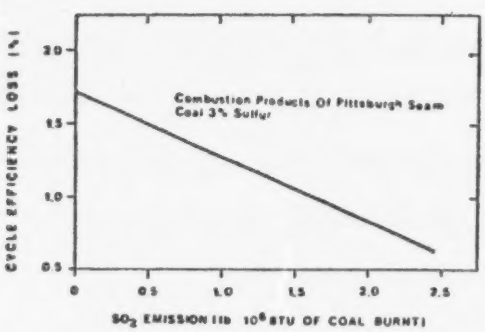


Figure 4.1.1-6 Change of Cycle Efficiency Loss with SO_2 Emmissions Level (Bergman, et al., 1977)

As has been stated before, the best method currently available for computing SO_x or other emissions from MHD's is the composite analytic models. One such model is the GPES system of the MIT Energy Laboratory which can be used to construct hypothetical systems, see Figure 4.1.1-7. Sample results are shown in Figure 4.1.1-8. There are several other such analytic models including those of Argonne National Labs, see Table 4.1.1-4. A crude parametric model of OCMHD emissions is shown in Figure 4.1.1-9.

4.1.2 Nitrogen Oxides

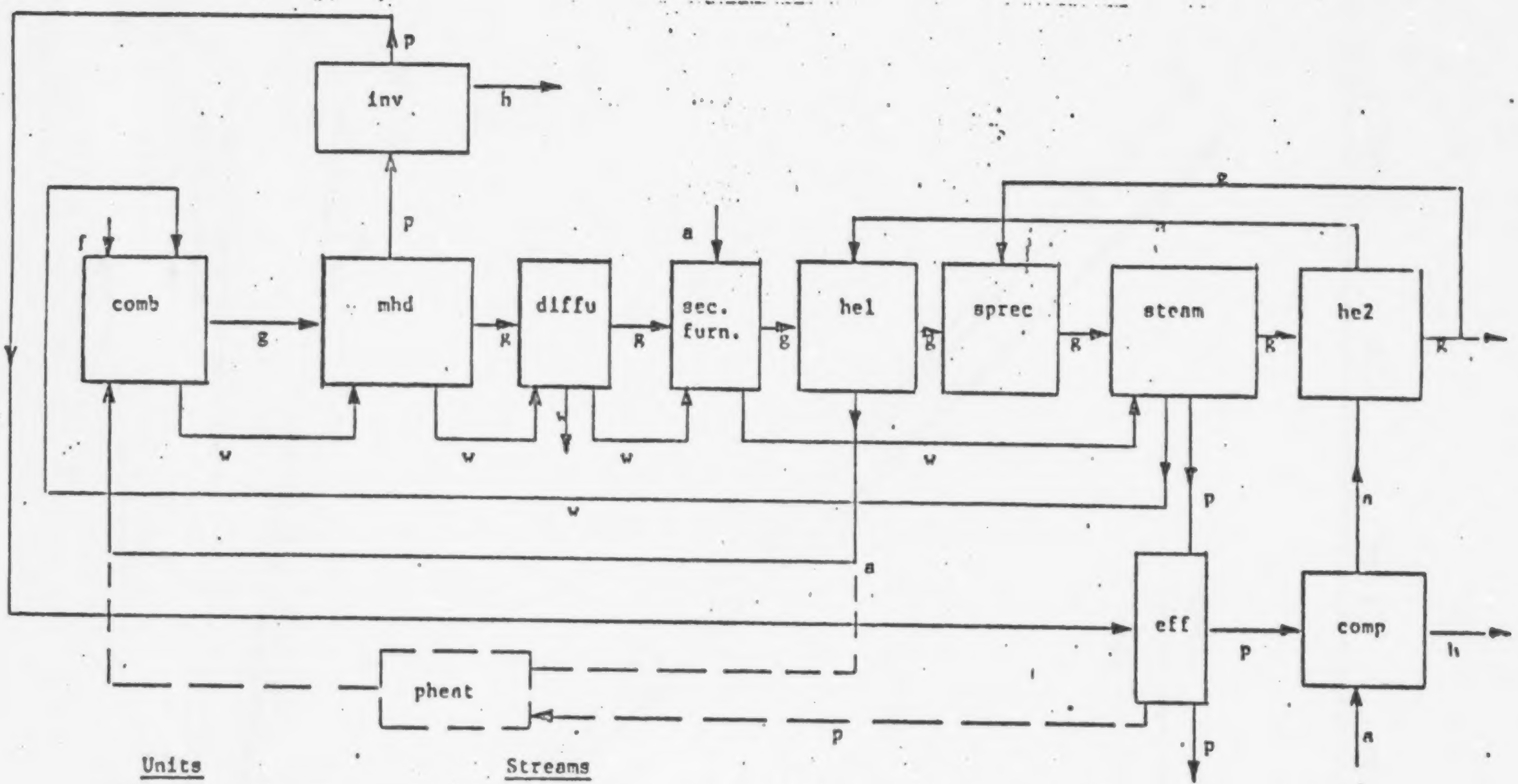
As can be seen in Table 4.1.2-1 there is a considerable variation in the estimated NO_x emissions from OCMHD. In the combustion of fossil fuels the process of nitric oxide formation is a function of temperature, see Figures 4.1.2-1 and 4.1.2-2. With the extremely high temperatures in OCMHD it might be possible to produce levels of NO_x emissions at almost 10 times those for conventional gas- and oil-fired plants, almost 10 times the current standard or 6.6 lbs $NO_2/10^6$ Btu (Beinstock, Demski, Demeter, 1971). Fortunately there are relatively easy methods of substantially reducing these NO_x emissions, namely:

(1) using two-stage combustion,

(2) maximizing NO_x production then scrubbing it out as a valuable fixed nitrogen source for fertilizers, or

(3) using pure oxygen instead of air for the combustion oxidant.

The first of these control options, two-stage combustion, not only reduces NO_x emissions but also can increase the power density by 10 to 20% by operating at 90% of stiochiometric air (Beinstock, Demski, Demeter, 1971). The measured NO_x values in a staged combustion simulation are shown in Table 4.1.2-2. Although it is not the intent of this review to deal explicitly with the various (6 to 60 reaction


inv
p
h
comb
f
g
mhd
p
diffu
sec. furn.
a
he1
sprec
steam
he2
g
w
a
eff
comp
phеat
p
h
a

Units

comb - combustor
comp - compressor
diffu - diffuser
eff - efficiency
he1,he2 - heat exchangers
inv - inverter
mhd - mhd-generator
pheat - pre-heater
sprec - seed-precipitator
sec.furn. - secondary furnace

Streams

a - air
f - fuel
g - combustion gas
h - heat
p - power
w - water

Figure 4.1.1-7 GPES Configuration for Open Cycle MHD Analytic Investigations

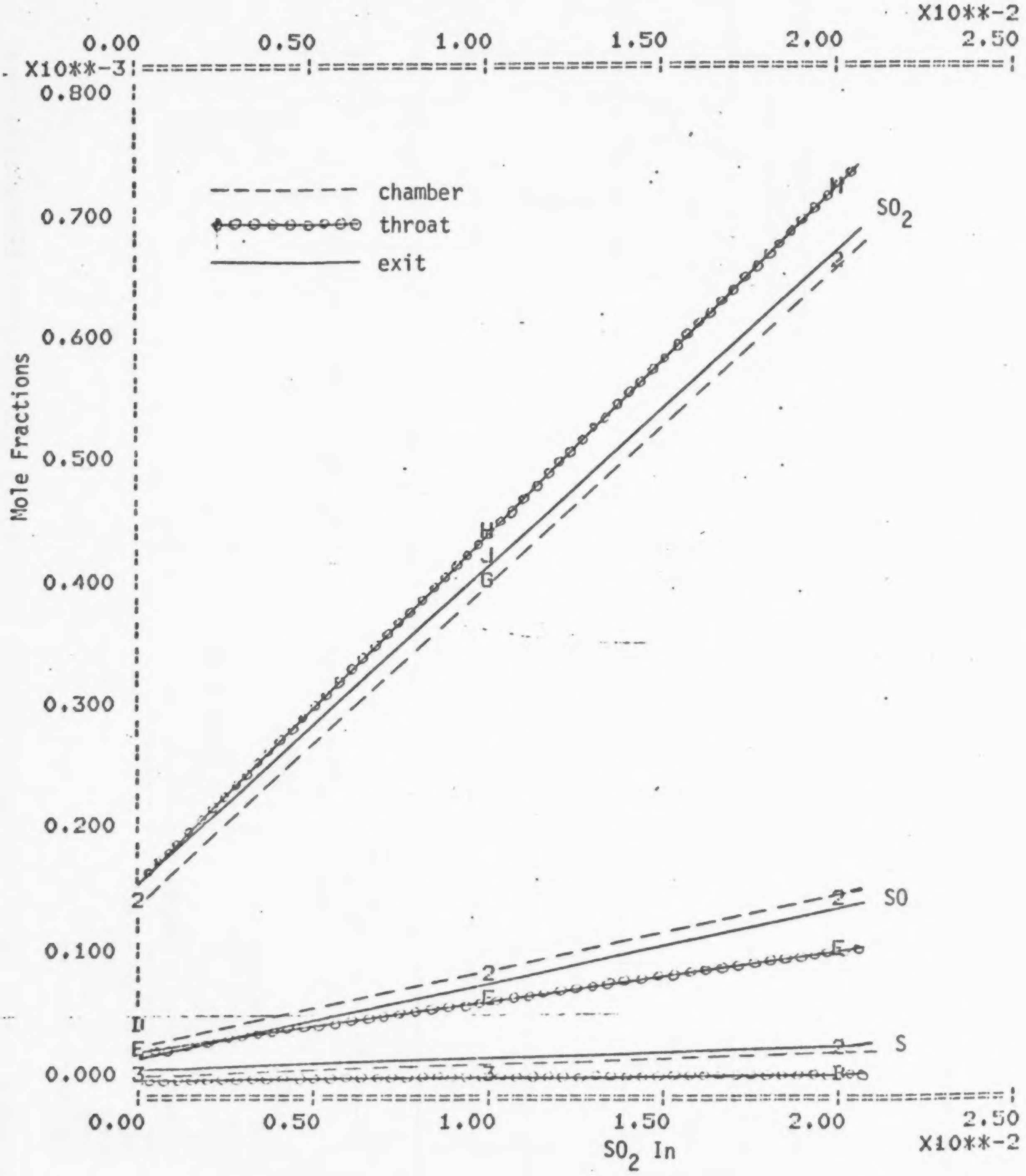


Figure 4.1.1-8 Sample Mole Fractions of Sulfur Compounds at Different Portions in MHD Cycle as Computed by GPES System

Table 4.1.1-4 Comparison of Equilibrium Conditions Between Computer Codes (Chung, Smith, 1977)

Parameter	Present Code		NASA Code
c_{pg}, average	.31	.33	Computed internally for each specie
Pressure, atm	4	4	4
Gas Temp., °R	4704	4598	4568
Average Molecular Wt.	29.5	29.6	29.5
Mass Fractions			
O_2	.020	.017	.012
CO	.035	.030	.028
CO_2	.2028	.2116	.2125
N_2	.692	.692	.674
NO	.0044	.0044	.0058
SO_2	.0021	.0021	.0020
H_2	.00021	.00021	.00018
H_2O	.0424	.0427	.0495
Ar	-	-	.011

Preheat temp., 1300°R

Stoichiometric Ratio, 1.0

Higher Heating Value, 11946 Btu/lb

Coal, Montana Rosebud with ash removed

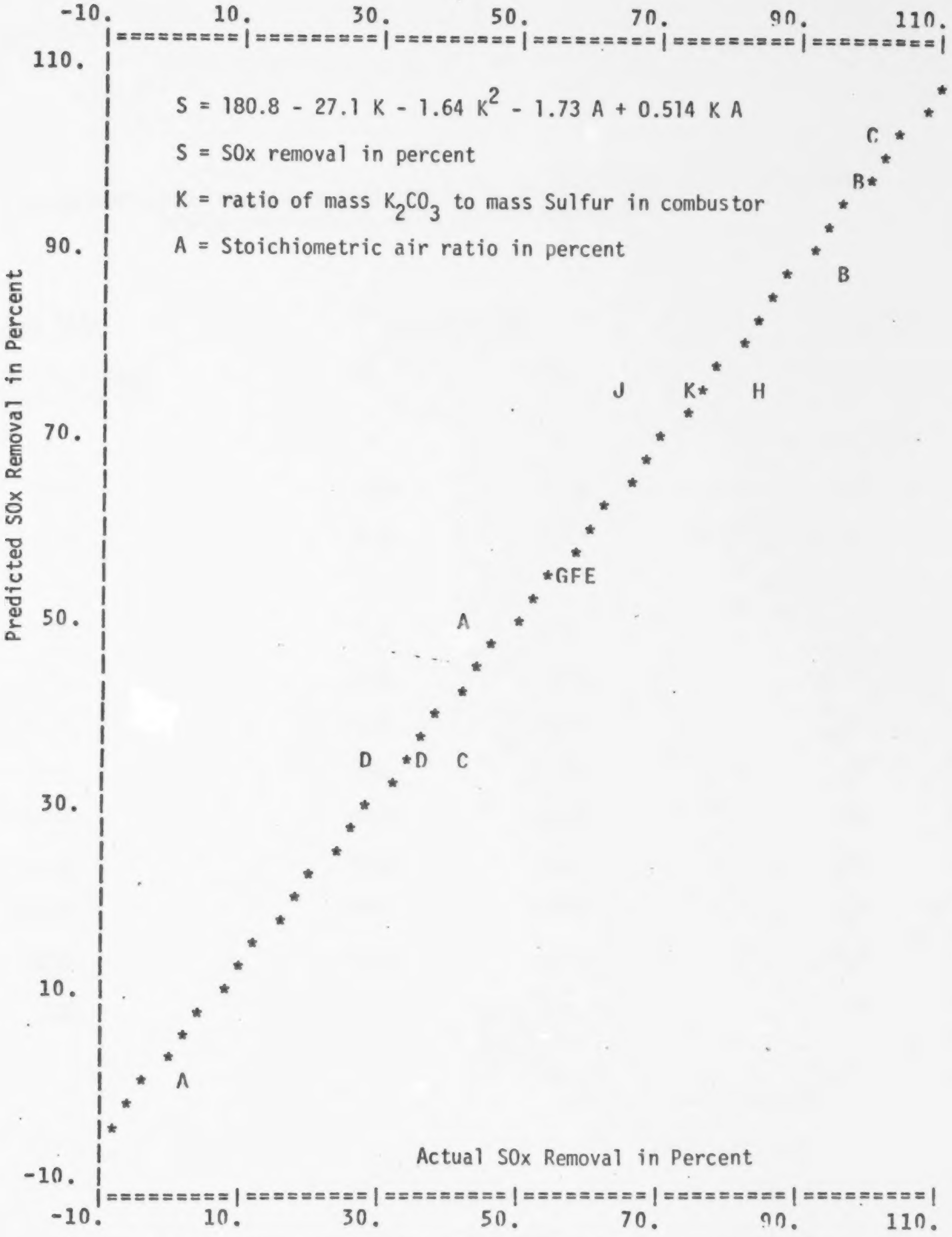


Figure 4.1.1-9 Very crude model of SOx removal based upon data from (Dicks,et al.,1977) and (Bienstock, et al.,1971).

TABLE 4.1.2-1
ESTIMATED NO_x EMISSIONS FOR OCMHD

Reference	lb/10^6 Btu input	ug/J	lb/kWh output	ppm
(General Electric, 1976) base case	0.3	0.129	.002	248
(General Electric, 1976) SRC	0.3	-	.0023	-
(Jackson, et al., Oct. 1976) Reference	less than 0.7	-	-	-
(Shaw, 1978)	0.71	0.304	-	585
(Folsom, 1978) Old EER set	0.72	0.309	-	595
(Folsom, 1978) New EER set	0.685	0.295	-	566
(Mori, Taira, 1972)	-	-	-	243
(Mori, Taira, 1973)	-	-	-	50
(Pepper, Eustis, Kruger, 1972)	-	-	-	283
(Penny, Bourgeois, Cain, 1977)	-	-	-	135-300
(Bienstock, et al., 1973)	-	-	-	150
(Hals, Lewis, 1972)	-	-	-	160-260
(REA, 1976)	-	-	-	155
(Shaw, Cain, 1977)	1.10g/kWht			2.3g/KWhe

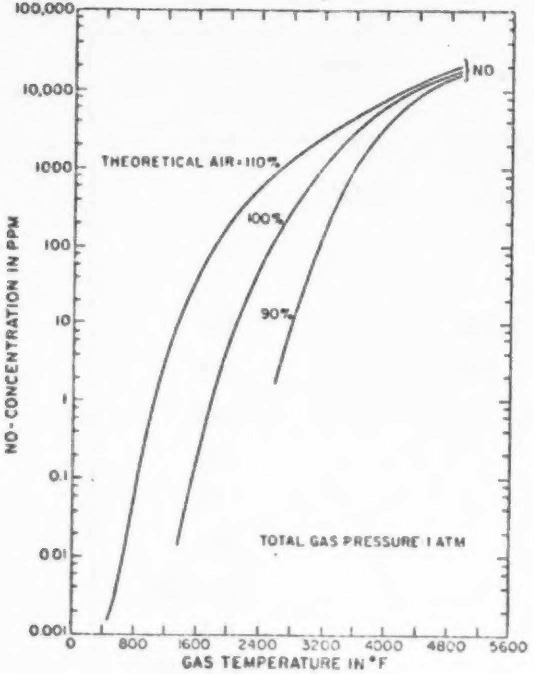


Figure 4.1.2-1 NO-Equilibrium Concentrations in Combustion Gases (Hals, Lewis, 1972)

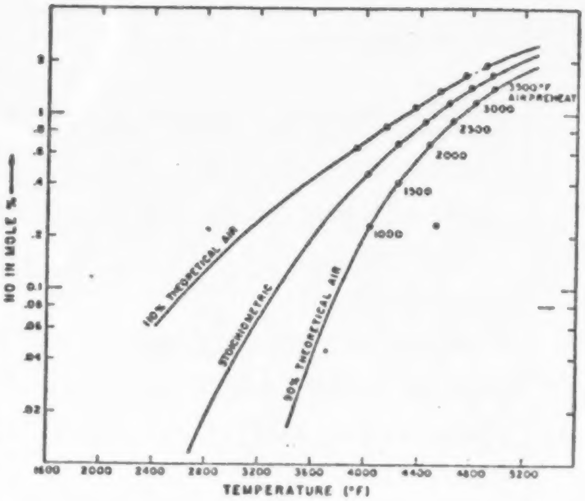


Figure 4.1.2-2 The Variation in Nitric Oxide (NO) Equilibrium Concentrations for Combustion Products From Coal with Air for Different Preheat Temperatures and Fuel-air Ratios (Hals, Jackson, 1969)

Table 4.1.2-2 NO_x Formation in 2-Stage Combustion (Bienstock, et al., 1973)

First Stage			Second Stage							
Sampling at 3500-3600 °F			Gas entrance temperature, °F				Effluent concentration			
% Stoichiometric oxygen	NO_x, ppm	CO vol-%	2000	2150	2450	2850	% Stoichiometric	NO_x, ppm	$\frac{\text{lb } NO_2}{10^6 \text{ Btu}}$	CO vol-%
110	4400	1.14					110	4086	3.13	0
102	2695	2.17					102	2612	2.00	0.1
101	2650	2.27					101	2225	1.70	0.4
95	880	4.30	x				106	150	0.12	0
94	782	6.61		x			103	351	0.27	0
94	727	6.90			x		105	550	0.40	0
92	543	8.11			x		107	575	0.43	0
92	496	7.53				x	107	885	0.66	0
91	496	9.95				x	104	885	0.64	0
88	356	10.40				x	104	814	0.59	0

equation) analytic models, some of this discussion is really in order to explain extrapolation of the results in Table 4.1.2-2 to large facilities. Comparisons of analytic models is therefore made at a couple of key points in their simulations.

Using principles of thermodynamic chemical equilibria and postulated kinetic mechanisms the principal concern of analytic models of NO_x emissions is the temperature-time-composition environments of the process. The tremendous amount of nitric oxide formed during combustion slowly decomposes to its elements. At some point in this process the mix is frozen and remains unchanged, and analytic models of the time-temperature history are aimed at estimating that freeze point.

In addition to a considerable amount of work at MIT there have been analytic models developed and used by:

(1) NASA-Lewis TRAN-72 (Patel, et al., 1976)
(2) US Bureau of Mines (Bienstock, et al., 1973)
(3) Avco (Hals, Lewis, 1972)
(4) Stanford (Pepper, Eustis, Kruger, 1972)
(5) Tokyo Institute of Technology (Mori, Taira, 1972)
(6) STD (Patel, et al., 1976)
(7) Exxon (Shaw, 1978)
(8) EER (Folsom, 1978)
(9) Argonne (Chung, Smith, 1977)

Comparisons of these models can first be made for the temperature-time profiles of their simulations, see Figures 4.1.2-3 through 4.1.2-7. Exact specification of the cooling rate is essential because high

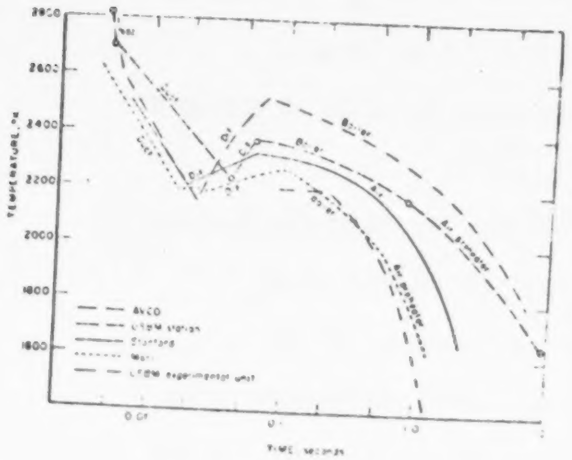


Figure 4.1.2-3 Temperature Profiles in MHD Plants (Bienstock, et al., 1973)

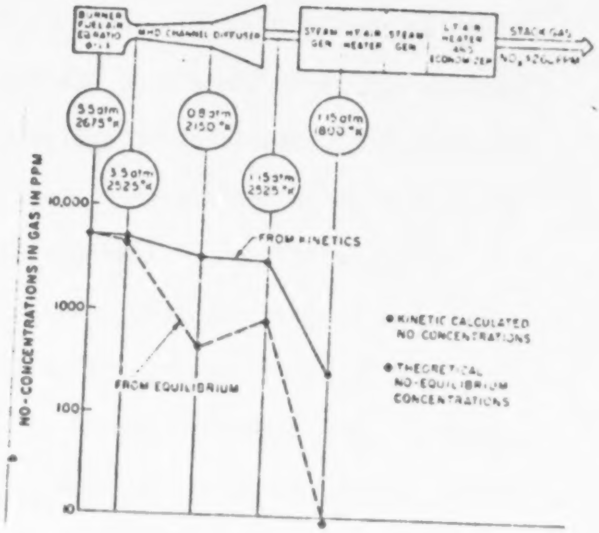


Figure 4.1.2-4 MHD-Steam Power Plant with Two Stage Combustions for Control of Nitrogen Oxides. 200°F assumed Air Preheat Temperature (Hals, Lewis, 1972)

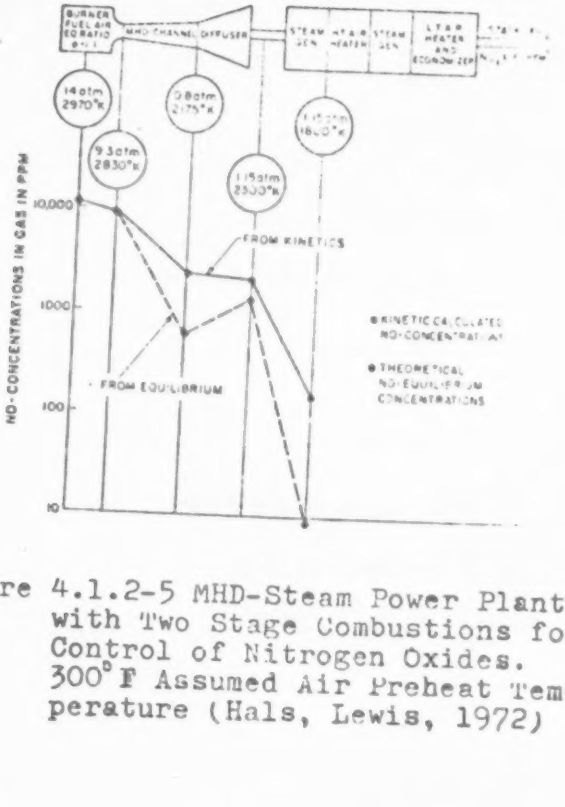


Figure 4.1.2-5 MHD-Steam Power Plant with Two Stage Combustions for Control of Nitrogen Oxides. 300°F Assumed Air Preheat Temperature (Hals, Lewis, 1972)

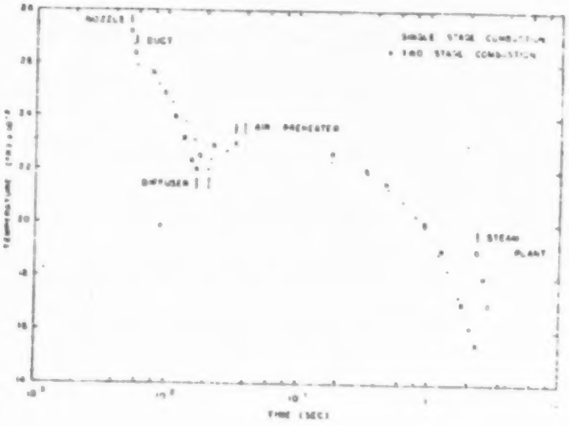


Figure 4.1.2-6 Temperature-Time History in OCMHD (Pepper, Eustis, Kruger, 1972)

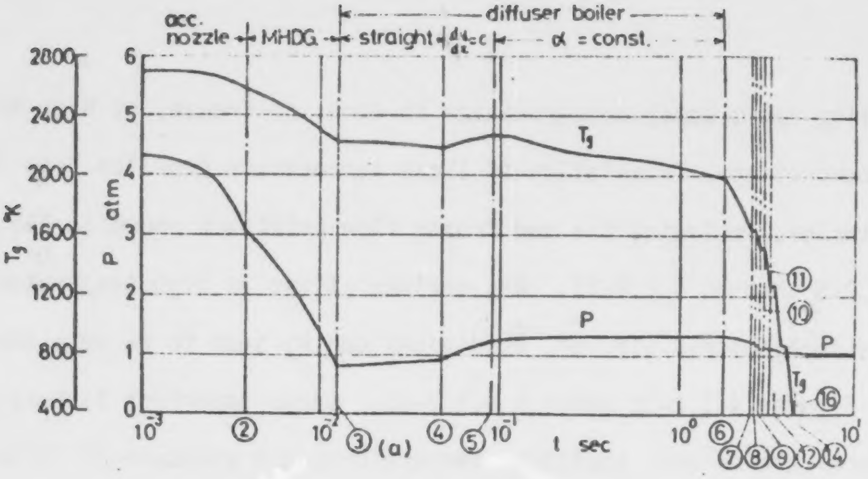


Figure 4.1.2-7 Analytic Results for Temperature-Time History (Mori, Taira, 1973)

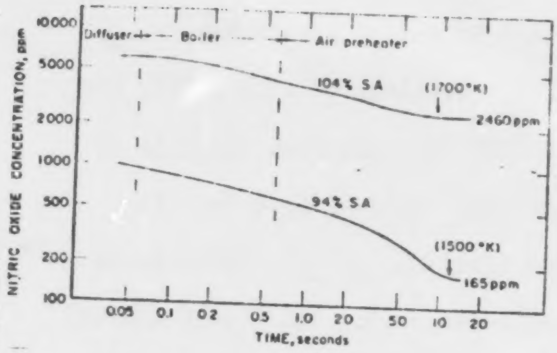


Figure 4.1.2-8 NO_x Levels in MHD Plant (Bienstock, et al., 1973)

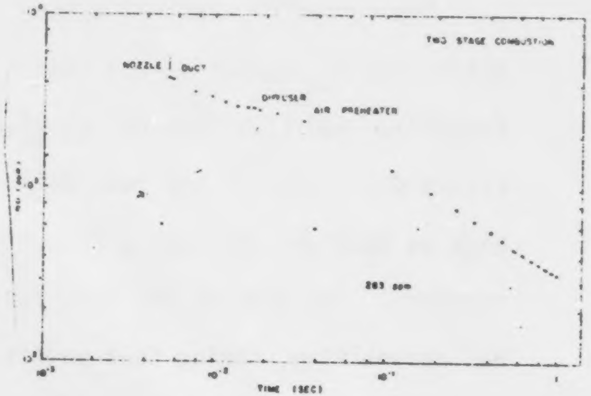


Figure 4.1.2-9 NO-Time History in OCMHD (Pepper, Eustis, Kruger, 1972)

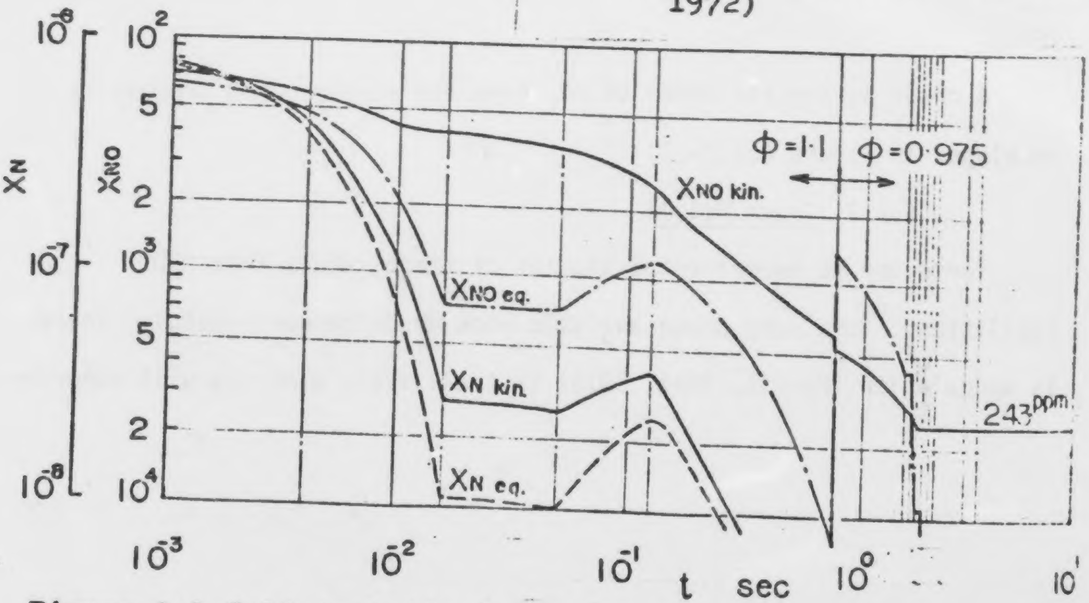


Figure 4.1.2-10 Analytical Results for the Optimized Power Plant, (Mori, Taira, 1973)

cooling rates cause decomposition to stop, or freeze, at high NO_x concentrations. Translation of these temperature profiles into NO_x histories, including the end frozen flow point are shown in Figures 4.1.2-8 through 4.1.2-11. Gas resident times at high temperatures and substiochiometric air, SA, conditions can be seen to be very important see Figures 4.1.2-12 through 4.1.2-15. Other important factors for NO_x control are method, position, temperature, and pressure of secondary air injection, with some illuminating sensitivity analysis on this subject shown in Table 4.1.2-3.

The second NO_x control scheme is now taken up, namely, that of maximizing NO_x formation and then scrubbing it out as a saleable fertilizer additive (Hoover, et al., 1976), (Cutting, et al., 1977), see Figure 4.1.2-16. It has been determined that NO_x emissions could be as high as 4800 ppm and that a Mitsui wet process could be best for its recovery. The process has been concluded (Cutting, et al., 1977) to be not competitive, losing four points in efficiency with 10% higher capital investment and cost of electricity. The third NO_x control scheme, use of pure oxygen, also is at a substantial cost disadvantage (Hals, Lewis, 1972).

A crude parametric model of NO_x from the staged OCMHD process is developed in Figure 4.1.2-17.

4.1.3 Trace Metals

There are no experimental studies of trace metals from MHD facilities. Some very crude analytic work would be very useful. There is speculation (Harris, Shah, 1976) that all trace elements will vaporize

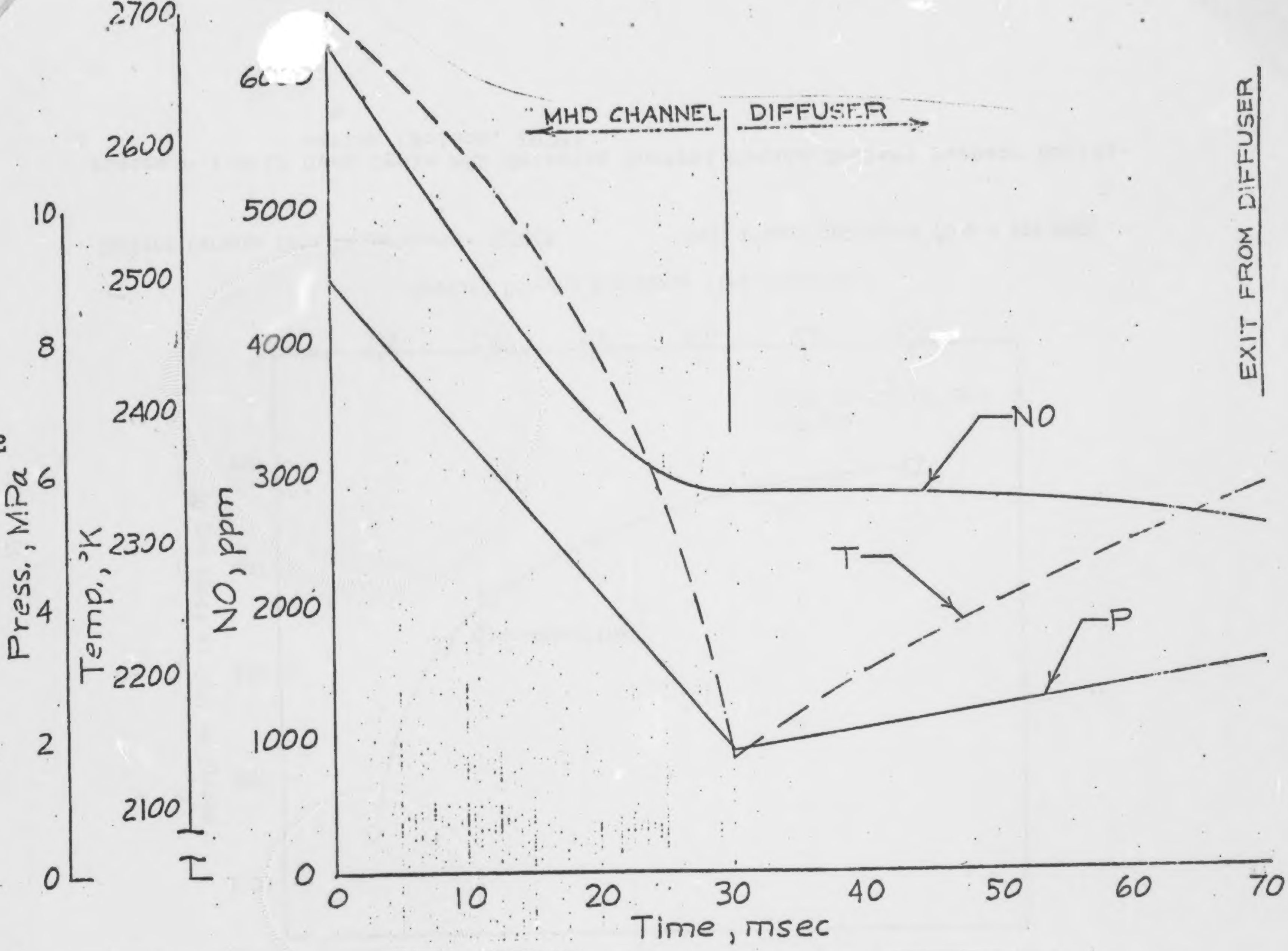
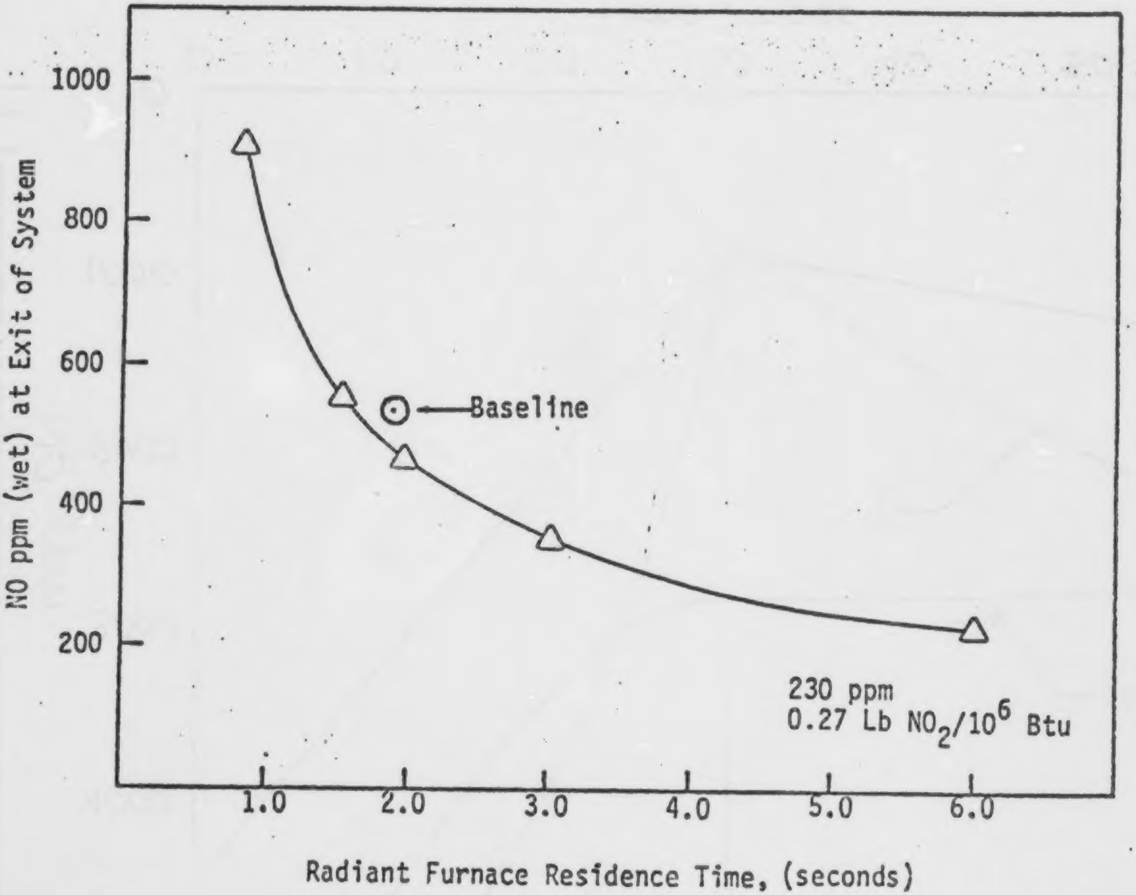


Figure 4.1.2-11 Property Variation Through Isentropic Channel - Diffuser from Other Research on this Exxon - EPA Contract



Radiant Furnace Exit Temperature = 1830°K　　Exit Plenum Residence Time = 221 MSEC

Figure 4.1.2-12 Open Cycle MHD Emission Control Option Radiant Furnace Modification (Folsom, 1978)

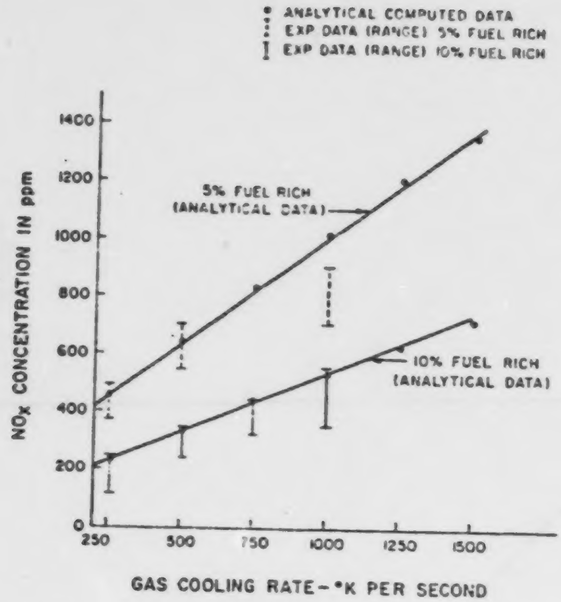


Figure 4.1.2-13 Final NO_x-concentrations in MHD Exhaust Gas According to Experimental and Analytical Data (Hals, Lewis, 1972)

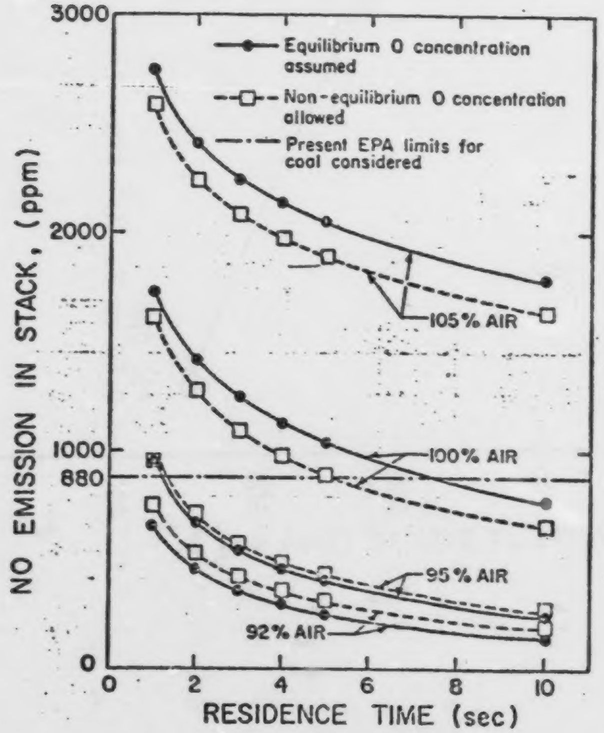


Figure 4.1.2-14 NO Emissions in an MHD Power Plant as a Function of Residence Time for the Radiant Boiler and Air Preheater Each (Jackson, et al., 1976)

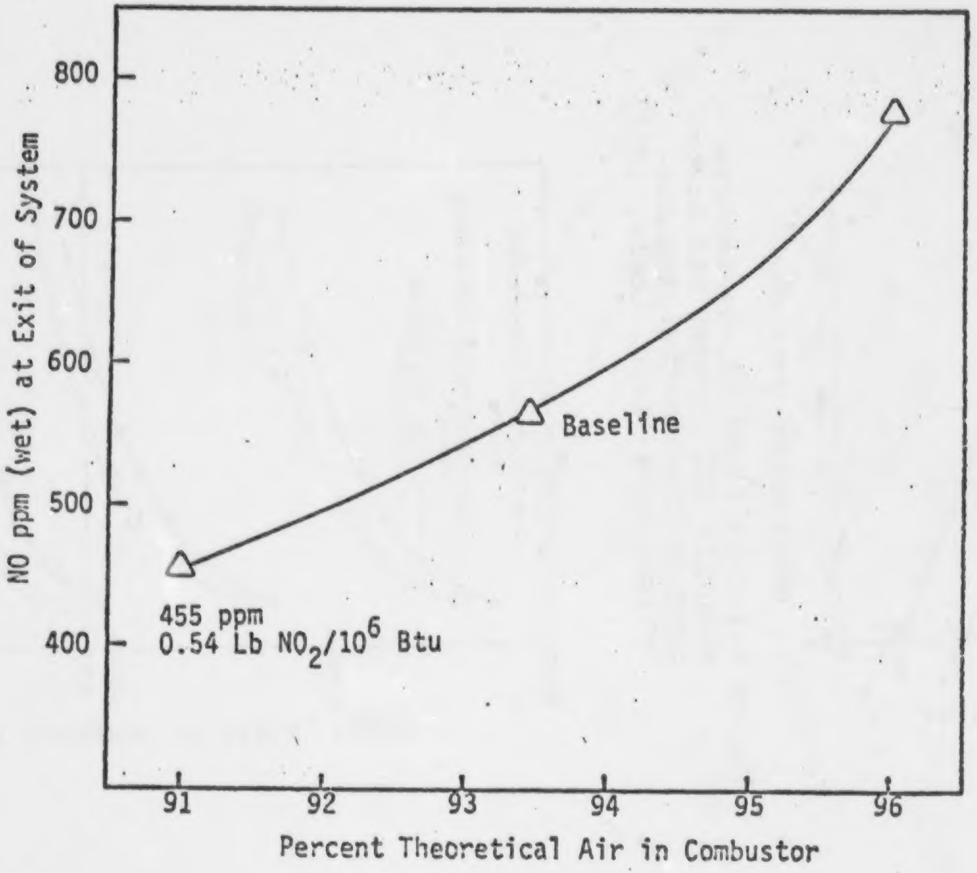


Figure 4.1.2-15 Open Cycle MHD Emission Control Option Stoichiometry Variation (Folsom, 1978)

Table 4.1.2-3 Open Cycle MHD Sensitivity of NO_x Emissions Estimates (Folsom, 1978)

SYSTEM MODIFICATION	NO CONCENTRATION AT END OF EXIT PLENUM (PPM)	PERCENT CHANGE FROM BASELINE
Baseline Configuration	566	0
MHD Channel Residence Time Reduced by Factor of Two	572 *	+ 1.06
Diffuser Residence Time Reduced by Factor of Two	568 *	+ 0.35
Linear MHD Channel Pressure Profile	566	0
Frozen Chemistry in Nozzle		
Combustor NO Concentration Reduced to Zero	565 *	- 0.18
Linear Temperature Profile in Radiant Furnace	590	+ 4.24
Radiant Furance Residence Time Increased by 0.5 sec.	516	- 8.83
Secondary Air Injection in Exit Plenum Delayed 0.5 sec.	417	-26.3
First Order Approximation of Radiant Furnace Three Dimensional Temperature Profile	677 *	+19.6

* NEW RESULT

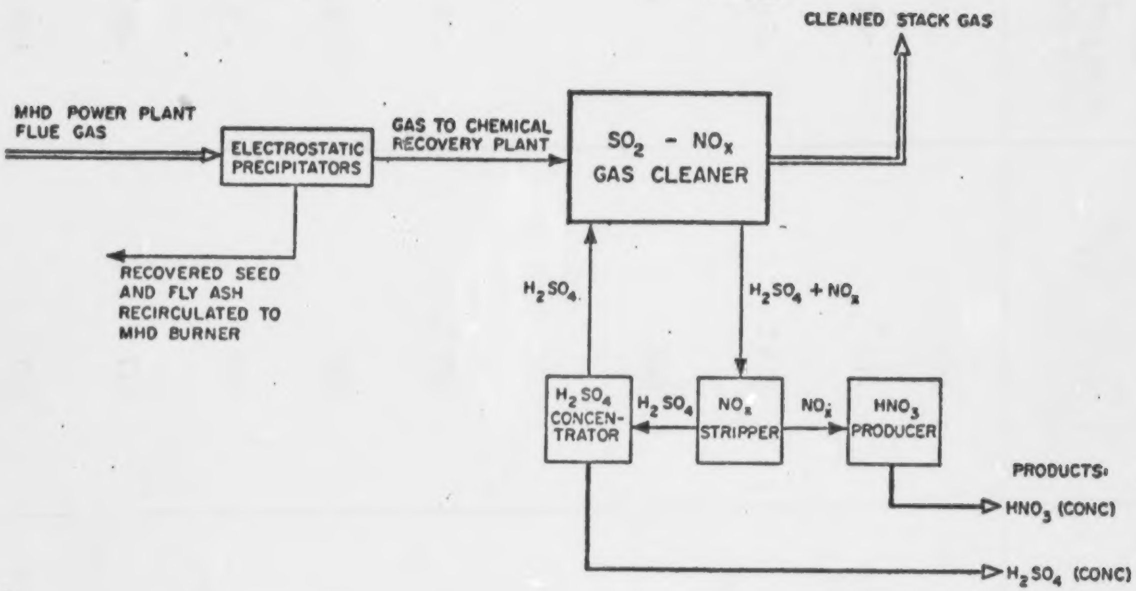

MHD POWER PLANT FLUE GAS
ELECTROSTATIC PRECIPITATORS
GAS TO CHEMICAL RECOVERY PLANT
$SO_2 - NO_x$ GAS CLEANER
CLEANED STACK GAS
RECOVERED SEED AND FLY ASH RECIRCULATED TO MHD BURNER
H_2SO_4
$H_2SO_4 + NO_x$
H_2SO_4 CONCEN-TRATOR
H_2SO_4
NO_x STRIPPER
NO_x
HNO_3 PRODUCER
PRODUCTS:
HNO_3 (CONC)
H_2SO_4 (CONC)

Figure 4.1.2-16 Fixed Nitrogen and Sulfur Recovery Process for Fossil Fueled MHD Power Plants (Hals, Jackson, 1969)

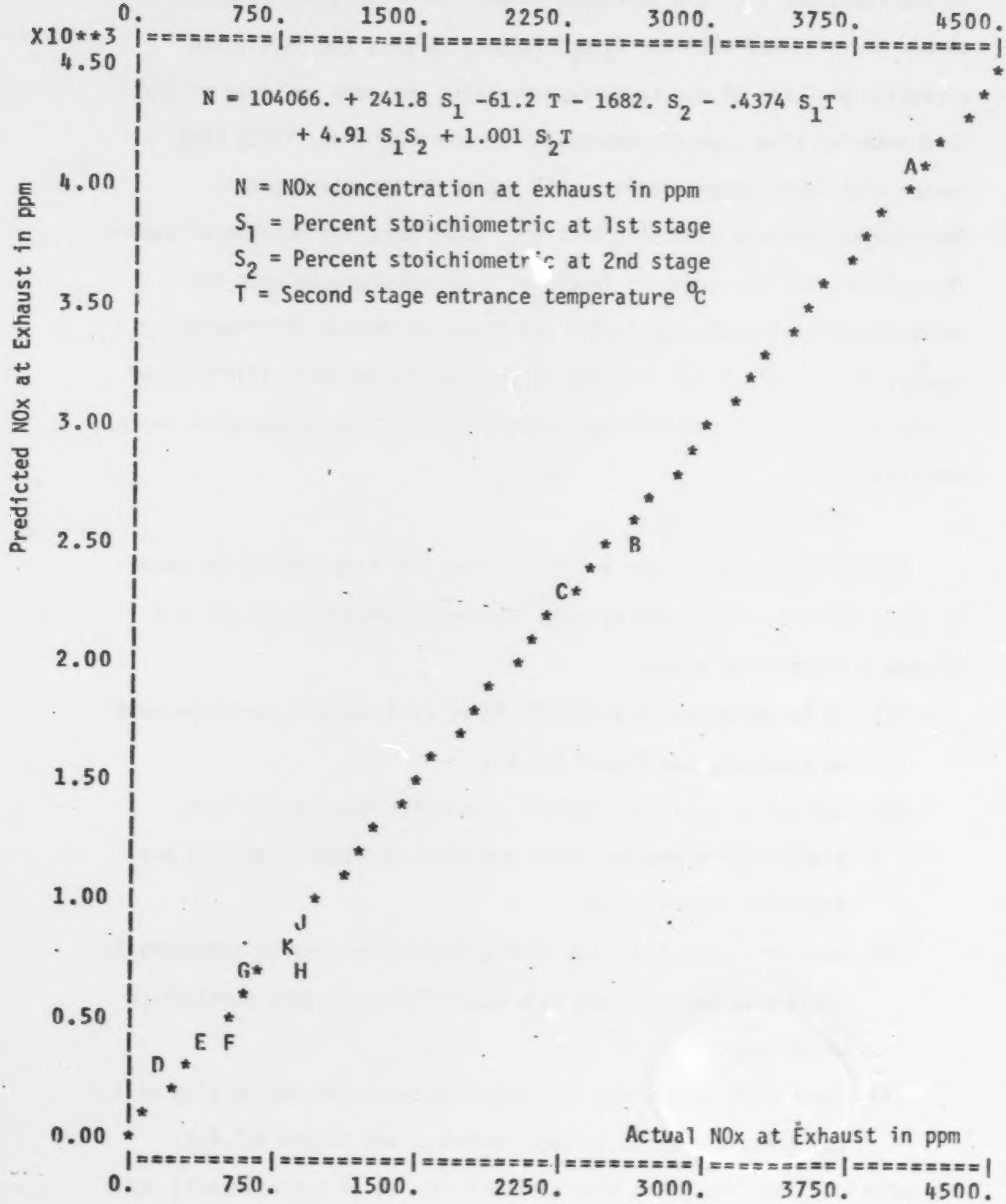


Figure 4.1.2-17 Very crude model of NOx exhaust from two-stage combustor based upon (Bienstock,et al.,1973) data.

in the combustor and form sulfates, oxides, chlorides, and fluorides and should be collected with the K_2SO_4. (Adding to this the inevitable corrosion products of the facility materials, and some refining of the seed material thus appears necessary.) In (Harris, Shah, 1976) they reason that 1% of these elements will appear in the stack gas. Considering particle size distributions, adhesions, and actions of vapors it could be that the eventual levels will be somewhere between the conventional coal combustor levels and these optimistic 99% removal levels, see Table 4.1.3-1. If any of the numbers in these fairly broad ranges are causes of concern then research ought to be directed at those sensitive areas.

4.1.4 Particulates

Estimates of particulate emissions from full-sized OCMHD are shown in Table 4.1.4-1. There are several reasons why particulates may not present a problem for OCMHD's:

(1) to be economically viable 99.5% of seed and ash particles must be captured, see Figure 4.1.4-1;

(2) mechanical cyclones, Venturi scrubbers, baghouse filters, electrostatic precipitators and other collection devices are available technologies;

(3) some pre-generation, hot-side precipitators may be necessary to avoid slag buildups and this would further reduce particulate emissions;

(4) combustion parameters that reject most of the ash as slag will pay great dividends in seed recovery, see Figure 4.1.4-2.

The materials that reach the precipitators consist of approximately 10% of the total coal ash and 50% of the K_2SO_4 formed in the flow (Harris, Shah, 1976).

TABLE 4.1.3-1

ESTIMATED TRACE METAL REMOVAL PERCENTAGES IN OCMHD

Element	Percent of Element Entering System That Is Removed Before Stack Emission
Antimony	25-99
Arsenic	60-99
Beryllium	25-99
Boron	25-99
Cadmium	35-99
Chromium	0-99
Cobalt	20-99
Iron	0-99
Lead	60-99
Manganese	0-99
Mercury	90-99
Selenium	70-99
Uranium	0-99
Vanadium	30-99
Zinc	28-99

TABLE 4.1.4-1

ESTIMATED PARTICULATE EMISSIONS FROM OCMHD

Reference	lb/10^6Btu input	lb/kWh output
(General Electric, 1976) base case	0.1	.0008
(General Electric, 1976) SRC	0.06	.00046
(Jackson, et al., Oct. 1976) reference	less than 0.1	-
(Shaw, Cain, 1977) total particulates	0.15 g/kWht	0.32 g/kWhe
(Shaw, Cain, 1977) fine particulates	-	-
(Harris, Shah, 1976)	0.1	.0007
(General Electric, 1976)	0.1	.0007
(REA, 1976)	0.1	-

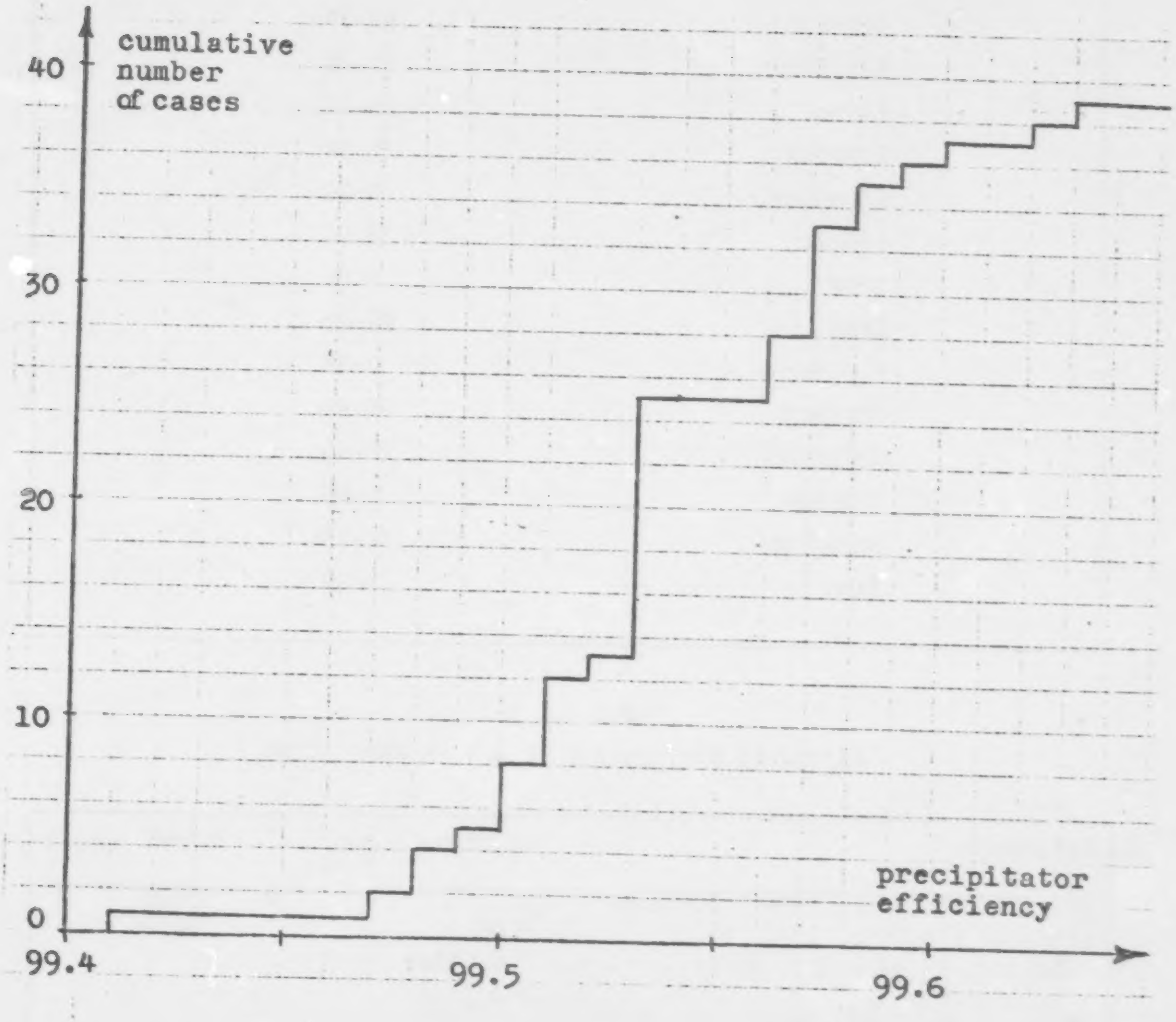


Figure 4.1.4-1 Precipitator Efficiencies for 39 Cases Investigated in Westinghouse Phase I ECAS Studies (Hoover, et al., 1976).

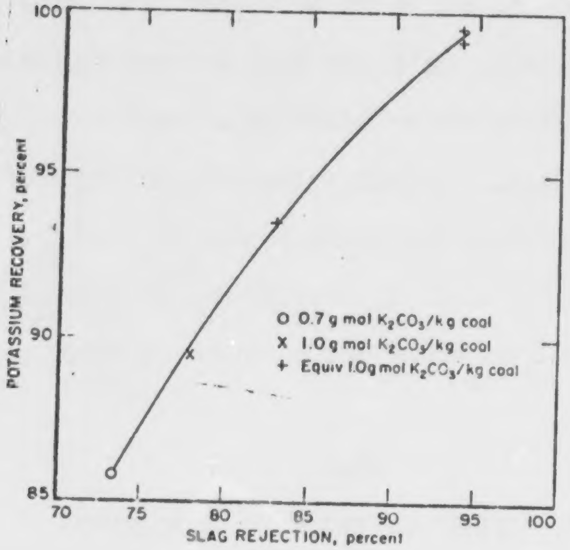


Figure 4.1.4-2 Potassium Recovery from Fly Ash Versus Slag Rejection in Combustor (Bienstock,et al.,1973).

A slightly different collection procedure may be required for peaking MHD's, but dust concentrations less than 0.01 grain/SCF are expected (Rosa, et al., 1970).

4.1.5 Other Air Emissions

Estimates of some of the other air emissions from OCMHD are given in Table 4.1.5-1. Thermal discharges to the air would be considerable in an MHD-Gas turbine design, but in the MHD-Steam these would be less than for conventional combustors, due to the greater expected efficiencies of MHDs. Although heat is the pollutant in air most positively correlated with excess mortalities, the heat dispersive potential of the atmosphere is considered so enormous that there have been considerations of pushing additional heat up the stack to increase the buoyancy of the MHD plume (Rosa, et al., 1970) for better disperson of the other gaseous and solid pollutants.

TABLE 4.1.5-1

OTHER AIR EMISSIONS FROM OCMHD

Heat to Air	
(General Electric, 1976) base case	606 Btu/kWh
CO	
(Shaw, Cain, 1977)	nil
(Bienstock, et al., 1971)	0
(General Electric, 1976)	0
(Hals, Lewis, 1972) with single stage	4.0%
(Hals, Lewis, 1972) with secondary stage	0.4 to 0.6%
Hydrocarbons	
(General Electric, 1976)	0
(Rosa, et al., 1970)	0

There is a considerable amount of CO created in the combustion process. The carbon monoxide concentrations exist in accordance with several equilibrium relationships including:

$$2CO_2 = 2CO + O_2$$

$$CO + H_2O = CO_2 + H_2.$$

The fraction of CO in these chambers can be as much as 10.4%, see Table 4.1.2-2. In the OCMHD design currently of interest, however, this CO is completely oxidized in the second stage, see again Table 4.1.2-2.

There is no expectation for MHD exhaust to contain any unburned fuel or hydrocarbons (Rosa, et al., 1970).

Noise from an MHD facility will be less than that from gas turbines of the same power (Rosa, et al., 1970). With the secondary heat recovery cycles attached there should be sufficient suppression of noise so that no additional attenuation will be necessary.

4.2 Emissions to Water

Table 4.2-1 shows estimates of some of the water wastes and emissions from OCMHD facilities. Figure 4.2-1 indicates the substantial reduction in thermal emissions to water from OCMHD. The principal reason for this amount can be seen to be the higher expected efficiency of these facilities. Quantifications have not been attempted of what amounts of total suspended solids, oil, grease, copper, iron and other heavy metals might be released to the water system supporting the OCMHD facility.

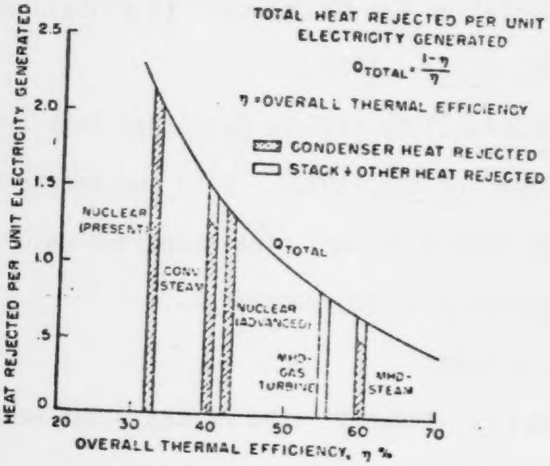


Figure 4.2-1 Effect of Power Generation Efficiency upon Thermal Pollution (Bienstock,et al.,1971).

TABLE 4.2-1
ESTIMATES OF WATER EMISSIONS FROM OCMHD

Heat to Water	
(General Electric, 1976) base case	2468 Btu/kWh
(Harris, Shah, 1976)	2377 Btu/kWh
(General Electric, 1976) SRC	2040 Btu/kWh
Waste Water	
(Shaw, Cain, 1977)	0.051 kg/kWhe
(Harris, Shah, 1976)	0.75 lb/kWh
(General Electric, 1976)	0.09 lb/kWh
Liquid Waste	
(Shaw, Cain, 1977)	24.60 g/kWht
(Shaw, Cain, 1977)	51.0 g/kWhe

4.3 Solids and Resources

The ash wastes shown in Table 4.3-1 are just slightly under the total ash that comes in with the coal. The same is true of the sulfur output shown in Table 4.3-2. The coal input to the plant is held outside in a 60-day supply pile; seed material is held inside. Slag and other wastes are held temporarily onsite before trucking to disposal. With holding ponds and all of this storage for the 30-year life of the plant it can be seen why the plant land requirements are only a small fraction of the total land requirements once disposal needs are considered.

4.4 Other Fuel Cycle Effects

The effects of coal extraction and transportation, facility construction, aesthetics, and other indirect environmental consequences of MHD plants will be very similar to those consequences for conventional

TABLE 4.3-1

ESTIMATES OF SOLID WASTES FROM OCMHD

Furnace Solids	
(General Electric, 1976)	.0534 lb/kWh
Fly Ash	
(General Electric, 1976)	.006 lb/kWh
(Shaw, Cain, 1977)	0.029 kg/kWh
(Harris, Shah, 1976)	0.058 lb/kWh
Total	
(Shaw, Cain, 1977)	14.01 g/kWht
(Shaw, Cain, 1977)	29 g/kWhe
(General Electric, 1976)	0.082 lb/kWh

TABLE 4.3-2

CONSUMPTION OF NATURAL RESOURCES AND SOLIDS

Land (acres/100 MWe)	
(General Electric, 1976) base case main plant	3.71
(General Electric, 1976) SRC main plant	3.71
(Harris, Shah, 1976) main plant	5.1
(Harris, Shah, 1976) disposal land	84.0
(Hoover, *et al.*, 1976) main plant	11.64 to 24.38
(Hoover, *et al.*, 1976) disposal land	11.36 to 14.75
(Hoover, *et al.*, 1976) railroad access	23.05 to 28.13
Total Water (gal/kWh)	
(General Electric, 1976) base case	0.22
(General Electric, 1976) SRC	0.21
(Shaw, Cain, 1977)	0.727 kg/kWhe
(Harris, Shah, 1976) disposal land	0.33
(Hoover, *et al.*, 1976)	0.530 to 0.612
Cooling Water (gal/kWh)	
(General Electric, 1976) base case	0.22
(General Electric, 1976) SRC	0.21
(Harris, Shah, 1976)	0.32
(Hoover, *et al.*, 1976)	0.516 to 0.596
K_2SO_4 Seed Material	
(Shaw, Cain, 1977)	.00059 kg/kWh
(Harris, Shah, 1976)	.00120 lb/kWh
(Hoover, *et al.*, 1976)	.00027 to 00535 lb/kWh
Sulfur Output	
(Shaw, Cain, 1977)	11.4 g/kWhe
(Shaw, Cain, 1977)	4.60 g/kWht
(Harris, Shah, 1976)	0.021 lb/kWh
Coal Input	
(General Electric, 1976) base case	0.65 lb/kWh
(General Electric, 1976) SRC	0.71 lb/kWh
(Shaw, Cain, 1977)	0.297 g/kWhe
(Harris, Shah, 1976)	0.655 lb/kWh
(Hoover, *et al.*, 1976)	0.65 to 1.07 lb/kWh

coal-fired facilities. There are computer programs that can be used to simulate some of these effects, such as direct fuel cycle effects from MERES at Brookhaven National Labs or indirect national environmental effects from SEAS at U.S. Environmental Protection Agency. A listing of some of these general impacts from coal-fired facilities can be found in (Jahnig, Shaw, 1977).

5.0 Conclusions

There is considerable trade-off potential between the various performance measures for OCMHD power plants. As such there is little doubt that current source emission standards, or even stricter standards, could be met. As increased demands are put on various aspects of OCMHD performance, however, the ultimate performance measure that is likely to suffer is economic cost. And thus the eventual market penetration of this technology will depend directly upon the comparative degree to which the costs have been held in line after all the problems have been solved and the emission and resource constraints met.

Some of the problems that have been perceived to most severely tax that ultimate performance measure are, in order of priority:

(1) considerable variations in types and severity of problems at different facility sizes;

(2) short life of materials exposed to exhaust gases and particulates, particularly electrodes and insulators, and the mutual compatibility of the materials under thermal cycling;

(3) slag coating of components, particularly the heat exchangers, slag tapping techniques, and high slag rejection in combustion area;

(4) arcs in passage of currents through cooler layers, and power conditioning system;

(5) workable and durable air preheater;

(6) good uniform mixing and feed of air and fuel;

(7) suitability for reuse of regenerated seed, and homogeneous seeding with that regenerated material;

(8) cost of stable superconducting magnet system;

(9) durability of heat exchanger surfaces in secondary furnace;

(10) energy costs of seed recovery system;

(11) cost of seed losses, especially in the slag, and investment cost of seed regenerator;

(12) avoidance of excessive heat losses, and effects of necessary thermal gradients between superhot and supercool areas;

(13) workability of NO_x control;

(14) prediction, optimization, and maintenance of working fluid conductivity, particularly boundary layer and particulate influences, and feedback from channel to combustor;

(15) expense of integrated power plant control system;

(16) costs of high-temperature heat exchangers; and

(17) costs of coal drying and handling.

Although most of these problems are only indirectly related to emissions and energy efficiencies it is believed that the trade-offs involved in solving these problems will significantly affect those performance measures in the commercial OCMHD. To ensure that the most appropriate trade-off of cost versus emissions is reached it seems essential that emission standards be based upon power plant outputs, so investments in high MHD efficiencies are adequately rewarded.

From the standpoint of recommending future work in this area it would be desirable to have maintained an updated data base of MHD emissions and efficiency information. An ongoing project at MIT is concerned with putting together just such a data base for fluidized bed combustors. There are several advantages to having such data bases available for all of the advanced energy technologies:

(1) they can be used as design tools to search for attractive configurations and operating parameters, particularly those unexpected synergistic effects that could be identified and exploited;

(2) they can be a ready source of latest information on the performance of that energy cycle;

(3) analytical models can be systematically tested against such a data base to evaluate the gap between theoretical and experimental information; and finally,

(4) they can be used to systematically identify and quantify the need for key pieces of information that are now inadequately known.

This final objective is perhaps the most important in that it could be a mechanism for developing R&D strategies.

6. References and Bibliography

Alad'ev, I.T., *et al.*, 1969. "Studies of Liquid-Metal MHD Cycles at the Krzhizhanovskii Power Institute," Tenth Symposium on Engineering Aspects of Magnetohydrodynamics, Cambridge, MA, pp. 39-40, March 26, CONF-690348.

Alyautdinov, R.A., *et al.*, 1974. "Computer Model of the U-25 Installation," Colloquium on the Problems of MHD Energy Conversion, Moscow, pp. 233-239, February, CONF-740242.

Amend, W.E., *et al.*, 1975, "Investigation of Two-Phase Liquid-Metal Magnetohydrodynamic Power Systems," Argonne National Lab., Argonne, Ill., 14 p., CONF-750810-1.

Amend, W.E., 1975. "Open Cycle MHD Systems Modeling Studies," Argonne National Lab., Argonne, Ill., 13 p., CONF-750669-2.

Annen, K.D., R.H. Eustis, 1977. "MHD Systems with Low Cooling Requirements," 16th Symposium on Engineering Aspects of MHD, Pittsburgh, PA, May 16-18.

Argyropoulos, G., 1976. "Magnetohydrodynamic (MHD) Cycles for Electric Power Generation," Issue paper to U.S. Senate Office of Technology Assessment.

Atomic Energy Review, 1972. "MHD Electrical Power Generation -- 1972 Status Report," Vol. 10(3), pp. 304-361.

AVCO Everett Research Lab., Inc., 1970. "Study of MHD Power System Burning Char with Oxygen," Everett, MA., 27 p., Feb. DI-14-32-0001-1201. PB-235-776.

AVCO Everett Research Lab., Inc. 1974. "Development Program for MHD Power Generation," Interim Technical Report, Everett, MA, 250 p., June.

Bates, J.L., 1976. "Characterization and Evaluation of Materials for the US-USSR MHD Program," Quarterly Report, Battelle Pacific Northwest Labs., Richland, WA, 70 p., January-March, BNWL-2004-2.

Beecher, D.T., *et al.*, 1976. "Energy Conversion Alternatives Study (ECAS), Westinghouse, Volume III. Summary and Advanced Steam Plant with Pressurized Fluidized Bed Boilers," Westinghouse Research Labs., Pittsburgh, PA, November. PB-268-558. NSF/RA-760590.

Beecher, D.T., 1975. "Study of Advanced Energy Conversion Techniques for Utility Applications Using Coal and Coal-Derived Fuels," Westinghouse Report No. 75-9E9-ECAS-R1, pp. 4-43.

Bergman, P.D., D. Bienstock, 1973. "Mixed Potassium-Cesium Seeding in Open-Cycle MHD Power Generation," 13th Symposium for Engineering Aspects of MHD, Stanford, March.

Bergman, P.D. *et al.*, 1975. "Conceptual Design and Economics of an MHD Pilot Plant," Intersociety Conference on Energy Conversion, Newark, Delaware, pp. 512-23, August.

Bergman, P.D., D. Bienstock, 1976. "Utilization of Western Coal for MHD Energy Conversion," 15th Symposium on Engineering Aspects of MHD, Philadelphia, PA, May 24-26.

Bergman, P.D., D. Bienstock, 1977. "Economic and Energy Considerations in MHD Seed Regeneration," 16th Symposium for Engineering Aspects of MHD, Pittsburgh, PA, May 16-18.

Bienstock, D., *et al.*, 1970. "High-Temperature Combustion of Coal Seeded with Potassium Carbonate in the MHD Generation of Electric Power," Bureau of Mines Report of Investigations 7361, 33 p.

Bienstock, D., *et al.*, 1971. "Environmental Aspects of MHD Power Generation," 1971 Intersociety Energy Conversion Engineering Conference, New York, pp. 1210-17.

Bienstock, D., *et al.*, 1973. "Coal Combustion Aspects of MHD Power Generation," Conference on American-Soviet Cooperation in the Field of MHD Power.

Bienstock, D., *et al.*, 1973. "Air Pollution Aspects of MHD Power Generation," Engineering Aspects of Magnetohydrodynamics, University of Mississippi, pp. vii.1.1-vii.1.10, March 26, CONF-730311.

Bienstock, D., *et al.*, 1974. "Coal Combustion Aspects of MHD Power Generation," Colloquium on the Problems of MHD Energy Conversion, Moscow, pp. 50-62, February, CONF-740242.

Blair, D., 1977. "Open Cycle MHD," Draft of Paper, Exxon Research and Engineering Co., Linden, N.J., April 12.

Bogdanova, T.N., *et al.*, 1973. "Study of the Energy Efficiency of Thermal Electric Power Stations with MHD Generators," Izv. Akad. Nauk SSSR, Ener. Transp. No. 5, pp. 143-9, Sept.-Oct.

Bohn, T., *et al.*, 1972. "Applied Magnetohydrodynamics Volume 10. MHD Experimental Installation AGRAS II: Description and Operating Experience," Kernforschungslanlage, Jeulich, 85 p., August. Jul-883-TP.

Brogan, T.R., 1963. "Electrical Properties of Seeded Combustion Gases," in *Progress in Astronautics and Aeronautics*, Vol. 12, pp. 319-345, Academic Press, New York.

Brogan, T.R., _et al._, 1974. "Preliminary Design of a Magnetohydrodynamic (MHD) Channel for the USSR U-25 Facility." Final Report. MEPPSCP, Inc., Boston, MA, 304 p., November. FE-1733-T-1.

Brouns, R.J., 1976. "Environmental Impacts of Nonfusion Power Systems," Battelle Pacific Northwest Labs, Richland, WA, 130 pp., Sept.

Brown. D.H., _et al._, 1976. "Energy Conversion Alternatives Study (ECAS). General Electric Phase II Final Report Volume I, etc..." General Electric Corporate Research and Development, Schenectady, NY, December. PB-268-466 NSF/RA-760582.

Brunsvold, A.R., E.S. Pierson, 1976. "Liquid-Metal MHD Coupled to Coal-Fired Fluidized-Bed Combustors," Argonne National Lab., Argonne, IL, 9 p., CONF-760556-1

Buende, R., J. Raider, 1973. "Designing MHD Generator Systems for Minimum Power Production Costs," Energy Convers. 13, No. 4, pp. 143-148, October.

Burkhart, J.A., _et al._, 1977. "Open-Cycle Magnetohydrodynamic/Steam System," in (NASA, 1977), pp. 201-245.

Carter, C., 1969. "Convective and Absolute Instabilities in an Open Cycle MHD Generator," in _Proc. Tenth Symp. on Engr. Aspects of MHD_, Mass. Inst. Tech., Cambridge, Mass.

Chung, P.M. and R.S. Smith, 1977. "An Analysis of a High-Temperature Coal Combustor According to a One-dimensional Flow Model," Argonne National Lab, ANL/MHD-77-2, October.

Corman, J.C. _et al._, 1976. "Energy Conversion Alternatives Study (ECAS). General Electric Phase II Final Report Volume I, etc...." General Electric Corporate Research and Development, Schenectady, NY, December. PB-268-466 NSF/RA-760582.

Corman, J.C., R.B. Fleming, L.P. Harris, and P.V. Pohl, 1976. "Energy Conversion Alternatives Study (ECAS), General Electric Phase I. Final Report, Vol. II, Advanced Energy Conversion Systems: Part 3, Direct Energy Conversion Cycles," NASA CR-134948-II-3, Feb.

Cutting, J.C., _et al._, 1977. "Open-Cycle Coal Burning MHD Power Plants for Commercial Service," 16th Symposium Engineering Aspects of MHD, Pittsburgh, PA, May 16-18.

Dicks, J.B., 1972. "MHD Central Power: A Status Report," _Mech. Eng._, p. 14, May.

Dicks, J.B., _et al._, 1974. "The Direct Coal-Fired MHD Generator System," 14th Symposium Engineering Aspects of MHD, April.

Dicks, J.B., *et al.*, 1974. "Direct Coal-Fired MHD Power Generation," J. Eng. Power, *96*, No. 2, pp. 153-157.

Dicks, J.B., *et al.*, 1975, 1976. "Development Program for MHD Direct Coal-Fired Power Generation Test Facility," Quarterly Progress Reports, Tennessee University, Tullahoma, TN, FE-1760-1, 2, 10, 22.

Dicks, J.B., *et al.*, 1977. "A Description of the Direct Coal-Fired MHD Facility at the University of Tennessee Space Institute," 12th IECEC, pp. 995-1003.

Dicks, J.B., *et al.*, 1977. "Investigation of Direct Coal-Fired MHD Power Generation," 16th Symposium Engineering Aspects of MHD, Pittsburgh, PA, May 16-18.

Dinelli, G., 1966. Effect of Various Parameters on the Efficiency of the MHD Power Stations," International Atomic Energy Agency, Vienna, Austria, 26 p., July 4, CONF-660704-54.

Donshoi, K.V., *et al.*, 1966. "Problems of MHD Conversion: Some Experimental Results," International Atomic Energy Agency, Vienna, Austria, 20 p., July 4, CONF-660704-56.

Duggan, J.L., Cloutier, R.J. (eds.), 1975. "Energy Sources for the Future. Proceedings of a Conference Held July 7-25, 1975 in Oak Ridge, TN," Oak Ridge Associated Universities, Inc., TN, 312 p., July. CONF-750733.

Edelston, B.S., E.S. Rubin, 1976. "Current and Future Use of Coal in the Northeast," Brookhaven National Lab., Upton, NY, 151 p., May, BNL-50560.

Electric Power Research Institute, 1975. "An Overall Program for the Development of Open Cycle MHD Power Generation," June, EPRI-SR-12.

Electric Power Research Institute, 1974. "EPRI/OCR Workshop on the Development of Open-Cycle MHD," Electric Power Research Institute and Office of Coal Research, Palo Alto, CA, May.

ERDA, 1974, 1975. "U-25 MHD Pilot Plant," Inst. Vysokikh Temperatur, USSR, ERDA-tr-102-P1, 2, 3.

ERDA, 1975. "Magnetohydrodynamics Power Generation and Theory," Technical information Center, Oak Ridge, TN, 875 p., November, TID-3356.

ERDA, 1975. "Second US-USSR Colloquium on Magentohydrodynamic Electrical Power Generation," Washington, D.C., 327 p. CONF-750669.

ERDA, 1976. "Third US-USSR Colloquium on MHD Electrical Power Generation," Moscow, USSR, October 20-21, CONF-761015.

Eustis, R.H., C.M. Kruger, 1975. "Atmospheric Pollution Aspects of Magnetohydrodynamic Power Plants," Stanford Univ., EPRI-110-FR, (PB-248 331), November.

Eustis, R.H., S.A. Self, 1975. "MHD Phenomena at High Magnetic Fields. Interim Technical Report July 1972 - December 1974," Stanford Univ. Dept. of Mechanical Engineering, Calif. 13 p., February. FE-1227-1.

Fabris, G., *et al.*, 1976. "Influence of Wall-Jet Gas Injection on Liquid-Metal MHD Generator Performance," Argonne National Lab., Ill., 8 p. CONF-760556-2.

Federal Register, 1971. "Standards of Performance for New Stationary Sources," 36(247), 24876-24895, December 23.

Feldman, H.F., *et al.*, 1970. "The Effect of Air/Fuel in the MHD-Generator on the Operation of an Open-cycle MHD-topped Power Plant," 10th Symposium on Engineering Aspects of Magnetohydrodynamics, Cambridge, MA, March 26-28.

Feldman, H.F., *et al.*, 1970. "The Effect of Air/Fuel in the MHD-Generator on the Operation of an Open-cycle MHD-topped Power Plant," Energy Conversion, Vol. 10, #2, April.

Feldman, H.F., Simons, W.H. and Bienstock, D., 1968. "Factors Affecting the Optimum Feeding Levels of Coal or Char Fired, Open Cycle MHD Power Plants," SM107/36, Electricity from MHD, IAEA, Vienna.

Feldman, H.F., *et al.*, 1970. "Kinetics of Recoverying Sulfur from the Spent Seed in an MHD Power Plant," Environmental Science and Technology 4(6), pp. 496-502.

Feldman, H.F., *et al.*, 1970. "Thermodynamic, Electrical, Physical, and Compositional Properties of Seeded Coal Combustion Products," Bureau of Mines Bulletin 655, Washington, DC.

Fishman, F., 1968. "Instability of Hall MHD Generators to Magneto-acoustic Waves," in 9th Symp. on Engr Aspects of MHD, Univ. of Tenn. Space Inst., Tullahoma, Tenn.

Flinders University of South Australia, 1974. "Physics and the Energy Industry," Bedford Park, Australia, January, CONF-740137, INIS-mf-2006.

Folsom, B.A., 1978. "Environmental Assessment of Advanced Energy Conversion Technologies," EER Corp. presentation to EPA-IERL, Cincinnati, OH, May 17.

Fushini, K. *et al.*, 1973. "Construction of a Small-scale MHD Test Plant (ETL MARK VI)," Engineering Aspects of Magnetohydrodynamics, Univ. of Mississippi, pp. iv-1.1-iv.1.6, March 26, CONF-730311.

Gadda, "Recent Experimental Results Relating to the Seeding of MHD Combustion Gases," SM107/207, in *Electricity from MHD*, IAEA, Vienna.

Gannon, R.E., S.K. Ubhayakar, C.W. Von Rosenberg, Jr., D.B. Stickler, and F.A. Hals, 1968. *Application of the Rapid Devolatilization of Coal in MHD Power Cycles*, Symposium on Engineering Aspects of MHD, VII.2.1.

Gaponov, I.M., L.P. Poberezhskii, 1975. "Study of the Electrical Conductivity of a Plasma in Combustion Productions, (An SSSR Moscow Inst. Vyspokikh Temperatur)," 45 p. ERDA-tr-186.

General Electric Company, 1975. "Study of Advanced Energy Conversion Techniques for Utility Applications Using Coal or Coal Derived Fuels," Vol. II, Oral Briefing on the Results of Task I at NASA Lewis Research Center, Cleveland, OH, May 20, NAS3-19406.

General Electric Company, 1976. "Comparative Study and Evaluation of Advanced Cycle Systems," General Electric Corporate Research and Development, Schenectady, NY, May. PB-254-392, EPRI/AF-158.

General Electric Company, 1976. "Energy Conversion Alternatives Study - ECAS - Phase 1," NASA, CR-134948.

General Electric Company, 1976. "Energy Conversion Alternatives Study, Phase II Report," NASA Report NASA-CR-134949, General Electric Co., Schenectady, NY, December.

General Electric Company, 1976. "Study of Advanced Energy Conversion Techniques for Utility Applications Using Coal or Coal Derived Fuels," General Electric Report, February 17.

General Electric Company, 1977. "Coal/Open-Cycle Magnetohydrodynamic/Steam System." in (NASA, 1977).

Gilbert Assoc. Inc., STD Research, 1976. "Baseline Power Plant Overall Plant Design Description," ERDA, MHD Power Generation Program, December.

Goldenburg, S.A., *et al.*, 1975. "Experimental Investigation of the Effect of the Excess Fuel Coefficient on the Electrical Conductivity of Potassium-seeded Hydrocarbon Fuel Combustion Products," Electricity from MHD, Vol. IV, Vienna, Austria, pp. 2239-2248, July 24.

Golyashevich, S.L. *et al.*, 1975. "Investigations of Coal Combustion for MHD Conversion of Energy," 6th International Conference on Magnetohydrodynamic Electrical Power Generation, Vol. II, Washington, DC, pp. 321-334, June 9, CONF 750601-P2.

Gubarev, A.V., I.G. Nosov, 1970. "Study of the Efficiency of Electric Power Generation at Thermal Electric Power Plants with Faraday-type Open-cycle MHD Generators," Institut Atomnai Energii, Moscow, USSR, IAE-2021.

Hals, F., L. Keefe, 1964. "A Method of Seed Recovery in Coal Fired MHD Power Plants," 5th Symposium on Engineering Aspects of Magnetohydrodynamics," Cambridge, MA.

Hals, F., W.D. Jackson, 1969. "MHD Power Generation: Economic and Environmental Implications," 10th Symposium on Engineering Aspects of Magnetohydrodynamics," Cambridge, MA, pp. 136-141, March 26, CONF-690348.

Hals, F., P. Lewis, 1972. "Control Techniques for Nitrogen Oxides in MHD Power Plants," Engineering Aspects of Magnetohydrodynamics, Argonne, IL, pp. VI.5.1.-VI.5.10.

Hals, F.A., et al, 1974. "Auxiliary Component Development Work at Avco Everett Research Laboratory Inc.," 14th Symposium on Engineering Aspects of Magnetohydrodynamics, Tullahoma, TN, pp. II.3/1-13, April 8-10.

Hals, F.A., et al., 1975. "Development and Design of High-Temperature Air Preheaters and Techniques for Emission Control of Nitrogen Oxides for Open Cycle MHD Power Systems," 6th International Conference on Magnetohydrodynamic Electric Power Generation, Vol. II, Washington, DC, pp. 267-288, June 9, CONF-750601-P2.

Harris, L.P. and R.P. Shah, 1976. "Energy Conversion Alternatives Study (ECAS) General Electric Phase II Final Report, Vol. II Advanced Energy Conversion Systems -- Conceptual Designs: part 3, Open Cycle Gas Turbines and Open Cycle MHD," NASA-CR 134949-II-3, December.

Hart, A.B., et al., 1964. "Some Factors in Seed Recovery," International Symposium on Magnetohydrodynamic Electric Power Generation, Vol. 3, pp. 1348-64, July 6-11.

Hauser, L.G., 1973. "Assessing Advanced Methods of Generation," Westinghouse Electric Co., Arch. Energiewirt., 17(20), pp. 989-999.

Heywood, J.B., G.J. Womack, 1969. Open-Cycle MHD Power Generation, Pergamon Press, Ltd.

Hoover, D.Q., et al., 1966. "Feasibility Study of Coal Burning MHD Generation," Westinghouse Research Lab., March, PB 235 460.

Hoover, D.Q., et al., 1976. "Energy Conversion Alternatives Study (ECAS), Westinghouse Phase I Final Report, Vol. III, Open-Cycle MHD," Westinghouse Research Labs., NASA CR-134941, 425 p., February.

Horn, G., and E.M. Hughes, 1967. "Engineering Aspects of Magnetohydrodynamic Power Generation," Trans. Inst. Chem. Eng., London, T-182-9, June.

Hughes, E., *et al.*, 1974. "Control of Environmental Impacts from Advanced Energy Sources," EPA, March, EPA-600/2-74-002.

Jackson, W.D., *et al.*, 1970. "Critique of MHD Power Generation," J. Eng. Power, 92, pp. 217-30, July.

Jackson, W.D., *et al.*, 1973. "Coal Fired MHD for Central Station Power Generation," 6th Annual Frontiers of Power Technology Conference, Stillwater, OK, pp. 4/1-17, October 10-11.

Jackson, W.D., *et al.*, 1974. "The Role of the Office of Coal Research in the National Program for MHD Development," in (NSF, 1974), pp. 17-26.

Jackson, W.D., *et al.*, 1975. "Consideration in the Development of Open Cycle MHD Systems for Commercial Service," 6th International Conference on MHD Electric Power Generation, Vol. V., Washington, DC, p. 21, June, CONF-75061-P5.

Jackson, W.D., *et al.*, 1975. "MHD Power Generation - Technology Status and Development Plan," Institute of Gas Technology Symposium, Chicago, IL, June 23.

Jackson, W.D., P.S. Zygielbaum, 1975. "Open Cycle MHD Power Generation - Status and Engineering Development Approach," American Power Conference, Chicago, IL.

Jackson, W.D., 1976. "MHD Electrical Power Generation: Prospects and Issues," AIAA 9th Fluid and Plasmadynamics Conference, San Diego, CA, July, AIAA 76-309.

Jackson, W.D., *et al.*, 1976. "Design Considerations for a Coal-Fired 2000 MW (th) Open Cycle MHD/Steam Baseload Powerplant," 3rd US-USSR Colloquium on MHD Electric Power Generation, Moscow, USSR, October 20-21.

Jackson, W.D., *et al.*, 1976. "Development of a Baseline Reference Design for an Open Cycle MHD Power Plant for Commercial Service," 15th Symposium on EAM, Philadelphia.

Jackson, W.D., *et al.*, 1976. "MHD Power Generation 1976 Status Report," IECEC, pp. 1006-1019.

Jackson, W.D., *et al.*, 1977. "Status of the Reference Dual-Cycle MHD-Steam Power Plant," 16th Symposium on Engineering Aspects of MHD, Pittsburgh, PA, May 16-18.

Jackson, W.D., et al., 1977. "Design of the Montana Magnetohydrodynamics Component Development and Integration Facility," 12th IECEC, pp. 988-994.

Jahnig, C.E. and H. Shaw, 1976. "Environmental Assessment of an 800 MWe Conventional Steam Power Plant," Exxon/GRU.1.DJAD.76, Exxon R&E, 54 pp., September.

Jedrzyowski, Zb., St. Andrzejewski, 1966. "Study of Cycle Diagrams of Power Plants with MHD Generators," International Atomic Energy Agency, 20 pp., July 4, CONF-660704-81.

Joint Publications Research Service, 1975. "First Joint Soviet-American Colloquium on the Problem of MHD Energy Conversion," JPRS-63794, 254 pp., January.

Joubert, J.I., et al., 1976. "Kinetics of Regeneration of Spent Seed from MHD Power Generation Systems," 15th Symposium on Engineering Aspects of MHD, Philadelphia, May 24-26.

Kantrowitz, A., R.J. Rosa, 1974. "MHD Power Generation," American Physical Society Topical Conference on Energy, Chicago, IL, February.

Kantrowitz, A., 1977. "The First 20 Years of MHD Development," Conference on High Temperature Sciences Related to Open-Cycle, Coal-Fired MHD Systems, Argonne, IL, pp. 289-298, April 4-6, ANL-77-21.

Karr, C., Jr., et al., 1974. "Composition of Fly Ash from a Coal-Fired MHD Generator with Potash Seed," J. Inst. of Fuel, Vol. 52, pp. 177-80.

Kiepeia, J.E. (ed.), 1975. "Sixth International Conference on Magnetohydrodynamic Electrical Power Generation," Vol. II, ERDA, Washington, DC, 336 p., June 9-13, CONF 750601-P1, P2, P3, P4, P5, P6.

Kirillia, V.A., et al., 1967. "The Prospective Economics and Thermal Efficiency of Large Scale Open Cycle MHD Stations," Phil. Trans. Roy. Soc. London Ser. A., 261, pp. 394-400, July 6.

Klepeis, J., and J.F. Louis, 1971. "Disk Generator Applied to Open Cycle Power Generation," Proc. of the 5th International Conf. of MHD Electrical Power Generation, Munich.

Kolb, G., et al., 1974. "Applied Magnetohydrodynamics No. 13. Theoretical Bases of MHD Energy Conversion with Combustion Gases," Inst. fuer Technische Physik, Kernforschungsanlage Juelich G. m.b. H., 215 p., March. Jul-1055-TP.

Kontos, J., 1969. "System Analysis and Simulation in Magnetohydrodynamics," NTIS # DEMO-69/2, May.

Kuehne, W.D., *et al*., 1972. "Applied Magnetohydrodynamics Volume 9. Calculation of the Characteristic Quantity of the Working Gas of the MHD-Combustion Gas Generator," Kernsforschungsanlage, Juelich, W. Germany, 124 p. Jul-874-TP.

Lane, J.A., 1974. "Outlook for Alternative Energy Sources," Energy Research and Development Administration, Washington, D.C., 36 p. CONF-75-614-1.

Levi, E., 1978. "MHD's Target: Payoff by 2000," IEEE Spectrum, pp. 46-51, May.

Lindsay, W.T., E.V. Somers, W.S. Emmerich, 1964. "Fixed Nitrogen By-Products in Open Cycle MHD Generators," Westinghouse Research Labs., CONF-640701-38, 7 pp.

Little, A.D., Inc., 1975. "Benefits/Costs of Advanced Power Cycle Research: A Mid-1974 Analysis," Final Report, Cambridge, MA, 83 p., December. FE-1756-1.

Louis, J.F., 1968. "Disk Generator," *AIAA Journal*, *6*, 9, p. 1674.

Louis, J.F., (ed.), 1971. "Open Cycle Coal Burning MHD Power Generation; An Assessment and a Plant for Action," MIT, Cambridge, MA, June.

Louis, J.F., 1974. "MHD: Systems and Characteristics," in (NSF, 1974), pp. 27-30.

Louis, J.F., 1975, 1976. "Critical Contributions in MHD Power Generation," Annual Report, Quarterly Reports, MIT, E(49-18)-2215 (ERDA), FE-2215-1, 2, 3.

Louis, J.F., *et al*., *Open Cycle Coal Fired MHD Power Generation*, Final Report for the Period 21 May (1971) - 31 May (1975), Dept. of Aeronautics and Astronautics, MIT, prepared for ERDA Fossil Energy Contract No. E(49-18)-1209, Vols. I and II.

Marston, C.H., *et al*., 1976. "MHD Generator Investigations," General Electric Company, Philadelphia, March (AD-A023 417), November (AD-A032 790).

McGrath, I.A., M.W. Thring, 1964. "Open Cycle Magnetohydrodynamic Power Generation," J. Inst. Fuel, 37, No. 287, pp. 525-30, December.

Migra, R.P., *et al*., 1976. "Comparative Evaluation of Phase I Results from the Energy Conversion Alternatives Study (ECAS)," NASA, February, NASA TMX-71855.

Millet, J., 1968. Electricity from MHD, Proceedings from Warsaw Symposium, pp. 2979-2990.

MIT, 1975. "Open Cycle Coal Fired MHD Power Generation," Final Report, Cambridge, MA, 701 p., July 31.

Mori, Y., "Cycle and Efficiency of Large Scale Open-Cycle MHD Power Plants", in *Proc. of 5th International Conf. on MHD Electrical Power Generation,* (Munich, 1971).

Mori, Y., T. Taira, 1972. "Kinetic Study of Oxides of Nitrogen in MHD Power Plants," Engineering Aspects of Magnetohydrodynamics, Argonne, IL, pp. VI.7.1-VI.7.6.

Mori, Y., T. Taira, 1973. "Reduction of No_x Concentrations in MHD Steam Power Plant Systems," 13th Symposium on Engineering Aspects of Magnetohydrodynamics, Stanford, CA, March.

Mori, Y., K. O. Atake, S. Irobe, and T. Taira, 1975. "Decomposition of NO on Alumina Surface under Reducing Conditions for Emission Control of NO in MHD Power Plants," CONF-750601-P1, pp. 61-76.

Mori, Y., *et al.*, 1975. "Prediction of NO Concentrations in MHD Power Plants by Axi-Symmetric Two Dimensional Analyses," Tokyo Inst. of Tech., CONF-750601-P1, pp. 77-89.

NASA Lewis Research Center, 1976. "Comparative Evaluation of Phase I Results from the Energy Conversion Alternatives Study (ECAS)," NASA TMX-71855, February.

NASA, 1977. "Evaluation of Phase 2 Conceptual Designs and Implementation Assessment Resulting from the Energy Conversion Alternatives Study (ECAS)," Cleveland, OH, NASA TMX-73515, April.

NSF, 1974. "NSF-OCR Engineering Workshop on MHD Materials," MIT, November 20-22.

Nedospasov, A.V., *et al.*, 1976. "Thermophysical and Electrophysical Properties of Combustion Products with Seed," Inst. Vysokikh Temperatur, Moscow, USSR, 68 p., September. ERDA-tr-183.

Novosadov, V.B., 1976. "Errors of Measurement of Plasma Temperature in MHD Generator Channels," 35 p., October. ERDA-tr-184.

Nowacki, P.J., 1968. "Recent Developments in the Direct Conversion of Heat into Electricity by Means of Magnetohydrodynamic Electrical Power Generation," Neue Tech., 1-, No. B1, pp. 3-24, February.

Olds, F.C., 1971. "SO_2 Control: Focusing on New Targets," Power Engineering 77(8), pp. 24-29.

Oliver, D.A., P.H. Byer, 1972. "Physical and Economic Models of an Open Cycle Coal Burning MHD Power Generation," Gas Turbine Laboratory Report No. 197, MIT, Cambridge, MA, June.

Patel, N.J., et al., 1976. "Influence of Coal Type and Drying upon MHD Power Plants and Components," 15th Symposium for Engineering Aspects of MHD, Philadelphia, PA, May 24-26.

Penny, M.M., et al., 1977. "Development Status and Environmental Hazards of Several Candidate Advanced Energy Systems," 12th IECEC, pp. 646-654 (also EPA/IERL-Ci-092, 1976).

Pepper, J.W., et al., 1970. "NO Concentrations in MHD Steam Power Plant Systems," 11th Symposium on Engineering Aspects of Magnetohydrodynamics, Pasadena, CA.

Pepper, J.W., et al., 1972. "NO Concentrations in MHD Steam Power Plant Systems," Engineering Aspects of Magnetohydrodynamics, Argonne, Illinois, pp. VI.6.1.-VI.6.5.

Pepper, J.W., C.H. Kruger, 1973. "Accurate Modeling of NO Decomposition in MHD Steam Power Plant Systems," Engineering Aspects of Magnetohydrodynamics, Univ. of Mississippi, pp. VII.2.1.-VII.2.3, March 26, CONF-730311.

Pepper, J. and O.S. Yu, 1974. "The Application of Open Cycle MHD in an Electric Utility System," Proceedings of NSF-OCR Engineering Workshop on MHD Materials, MIT, November 20-22.

Pepper, J.W., et al., 1974. "NO Concentrations in MHD Steam Power Plant Systems," 14th Symposium on Engineering Aspects of Magnetohydrodynamics, Univ. of Tennessee Space Inst., Tullahoma, TN, pp. 111.5/1-2, April 8-10.

Pepper, J.W., 1974. "Effect of Nitric Oxide Control on MHD-Steam Power Plant Economics and Performance," Stanford Univ. SU-IPR Report No. 614, December.

Pepper, J. and O.S. Yu, 1974. "The Application of Open Cycle MHD in an Electric Utility System," in (NSF, 1974) pp. 31-46.

Pepper, J.W., 1975. "Effect of Nitric Oxide Control on MHD-Steam Power Plant Economics and Performance," Stanford Univ., 127 p.

Petrick, M., et al., 1976. "Experimental Two-Phase Liquid-Metal Magnetohydrodynamic Generator Program," Argonne National Lab., Argonne, IL, 102 p., November, ANL/ENG 76-04.

Pomeroy, B.D., et al., 1978. "Comparative Study and Evaluation of Advanced Cycle Systems," General Electric, EPRI Report AF-664, February.

Poncelet, J., L. Lozano, 1968. "Chemi-ionization and MHD: The Effect of CO_2 and Additives," Electricity from MHD, Vol. IV, Vienna, Austria, pp. 2141-2159, July 24.

Powell, C.A., 1974. "Utility Requirements for MHD Power Generation," in (NSF, 1974), pp. 7-16.

Powell, E.M., R.C. Ulmer, 1974. "Controlling Emissions from Fossil-Fueled Power Plants, Combustion 45, No. 7, pp. 24-34, January.

Reeder, J., R. Buende, 1973. "Basic Equations and Fundamental Data for Combustion MHD Generators, " Max-Planck-Institut fuer Plasmaphysik, Garching Munich, R.F. Germany, 225 p., July. IPP-IV-60.

Research and Education Association, 1975. "Chapter 46, MHD Power Generation" in *Modern Energy Technology*, REA, New York, pp. 1359-1412.

Rikov, A.I., *et al*., 1975. "Development and Study of High Temperature Materials for Various Components of MHD Installations," Inst. Vysokikh Temperatur, Moscow, USSR, 51 p., ERDA-tr-185.

Rockwell International Corp., 1976. "MHD Combustor Design Study," Final Report, Rockwell International Corp. Rocketdyne Div., Canoga Park, Calif., 440 p. May. TID-27144.

Rosa, R.. *et al*., 1970. "Advanced Peaking Power Plants," 11th Symposium on Engineering Aspects of Magnetohydrodynamics, Pasadena, CA.

Rosa, R.J., 1975. "MHD Power Generation Development Program," AVCO Everett Research Lab., Everett, MA, 227 p., June. PB-243-233.

Rudins, G., 1974. "U.S. and Soviety MHD Technology: A Comparative Overview," Rand Corp., Santa Monica, CA. AD-A0004-614.

Sarofim, A.F., 1977. "Combustion and Characterization of Coal, "Conference on High Temperature Sciences Realted to Open-Cycle, Coal-Fired MHD Systems, Argonne, IL, April 4-6, ANL 77-21.

Seikel, G.R., *et al*., 1971. "The Potential of Nuclear MHD Electric Power Systems," NASA, 12 p., NASA-TM-X-67829. N71-24578.

Seikel, G.R., *et al*., 1976. "A Summary of the ECAS Performance and Cost Results for MHD Systems," 15th Symposium Engineering on Aspects of MHD, Philadelphia, May 24-26.

Seikel, G.R., and L.P. Harris, 1976. "A Summary of the ECAS MHD Power Plant Results," 3rd US-USSR Colloquium on MHD, Moscow, USSR, October 21-22, NASA TMX-73481.

Shaw, H., 1978. "Environmental Assessment of Advanced Energy Conversion Technologies," Exxon R&E presentation to EPA-IERL, May 17.

Shaw, H., W.C. Cain, 1977. "Environmental Considerations in Advanced Energy Conversion Technology Assessments," 12th IECEC, pp. 655-660.

Sheindlin, A.E., G.I. Rossievskii, 1972. "Analysis of Factors Influencing the Thermal Efficiency and Economic Vitality of Electric-Power Stations Using Open-Cycle MHD Generators," Foreign Technology Div., Wright-Patterson AFB, OH, 18 p., September, AD-753708.

Shumiatskii, B. Ya., et al., 1976. "Studies Conducted at the U-15 Facility (IV)," Inst. Vysokikh Temperatur, Moscow, USSR, 60 p., ERDA-tr-182.

Siniasky, N.A. and I.A. Yavorsky, 1968. "The Effect of Phase Changes in Mineralized Composition of the Inorganic Part of Natural Coals on the Electrical Conductivity of a Colloidal Plasma," Electricity from MHD, IAEA, Vienna, SM 107/186.

Solbes, A. S.W. Petty, 1977. "Progress in Channel Development for Direct Coal Fired MHD," 12th IECEC, pp. 1004-1014.

Somers, E.V., D. Berg, and A.P. Fickett, 1976. "Advanced Energy Conversion," in Annual Review of Energy-1976, pp. 345-368.

Sonju, O.K., J. Teno and T.R. Brogan, 1970. "Comparison of Experimental and Analytical Results for a 20-MW Driven Hall Configuration MHD Generator," 11th Symp. on Engr. Aspects of MHD, California Inst. of Tech., Pasadena, California.

Sporn, Philip, Arthur Kantrowitz, 1959. "Large Scale Generation of Electric Power by Application of the Magnetohydrodynamic Concept," Power, Vol. 103, pp. 62-65.

STD Research Corp., 1971, 1972, 1973, 1974. "Realistic Modeling and Performance Prediction of MHD Generator Channels," Progress Reports, Pasadena, CA, May 17, 1971, Febraury 16, 1972, March 16, 1973, January 15, 1974, FE-1211-T-1, 2, 3, 4.

STD Research Corp., 1977. "Open-Cycle MHD Systems Analysis," Annual Report, EPRI, March, RP-640-2.

Tager, S.A. and J.M. Henry, 1976. "Fuel and Combustion," US-USSR text on MHD.

TRW Defense and Space Systems Group, 1976. "TRW 25 MW/sub T/Staged MHD Coal Combustor Conceptual Design Study," Redondo Beach, CA, 363 p., June. TID-27145.

Tempelmeyer, E.D., et al., 1977. "Investigation of Factors Influencing Potassium Seed Recovery in a Direct Coal-Fired Generator System," 16th Symposium for Engineering Aspects of MHD, Pittsburgh, PA, May 16-18.

Teno, J., et al., "Research Studies and Development of MHD Generators and Accelerators," AVCO Everett Research Laboratory Report.

USSR Institute for High Temperatures, 1974, "Influence of Ash on the Operation of MHD Generator Channel in the U-02 Facility," 20 p. ERDA-66.

USSR Institute for High Temperatures, 1975. "Principal Results of Scientific Research Done for 1974," Moscow, 62 p. ERDA-tr-162.

Way, S., 1964. "MHD Power Generation," Combustion: 36, No. 3, pp. 34-41, September.

Way, S., 1967. "Problems of the Coal-Fired MHD Power Plant," in Advances in Plasma Dynamics, T.P. Anderson and R.W. Springer (eds.), Northwestern University Press, Evanston, IL.

Way, S., 1971. "MHD Power Plant for Early Realization," 5th International Symposium MHD, Munich, W. Germany, pp. 615-26, May.

Way, S., 1974. "Combustion Aspects of MHD Power Generation," Chapter 10, Combustion Technology, edited by H.B. Palmer and J.M. Beer, Academic Press, New York and London.

Westinghouse, 1976. "Energy Conversion Alternatives Study - ECAS - Phase 1," Vols. 1-12, NASA, CR-134941.

Witwer, J.G., 1976. "Costs of Alternative Sources of Electricity," Stanford Research Inst., Menlo Park, CA, July, PB-255-765.

Wu, Y.C.L., et al., 1968. "Two Terminal Connected Open Cycle MHD Generators," 9th Symp. on Engr. Aspects of MHD, Univ. of Tenn. Space Institute, Tullahoma, Tenn.

Wu, Y.C.L., et al., 1974. "On Direct Coal-Fired MHD Generator," 14th Symposium on Engineering Aspects of MHD, April.

Wu, Y.C.L., et al., 1975. "Experimental and Theoretical Investigation of a Direct Coal-Fired MHD Generator," 6th International Conference on MHD Electric Power Generation, Washington, DC, June 9-13.

Young, W.E., et al., 1967. "Recent Studies of Advanced Coal Burning Power Plants," 1967 Intersociety Energy Conversion Engineering Conference, pp. 485-492.

Young, W.E., et al., 1974-1975. "Magnetohydrodynamic Investigation for Coal-Fired Open Cycle Systems," Monthly Prog. Rep. 1-20, OCR Contract No. 14-32-0001-1540, Office of Coal Research, Washington, DC.

Appendix A MHD Economic-Environmental Simulation

A computerized model has been developed at the MIT Energy Laboratory that has the capability of simulating the siting of many technologies including MHD power plants. This model, AEGIS - Alternative Electric Generation Impact Simulator, can be obtained from James Gruhl, principal investigator, at the MIT Energy Laboratory. To date the sponsors have been New England Electric System (NEES), Bradley Schrader program manager, and Northeast Utilities Service Co. (NUSCO), Denning Powell and William Renfro program managers.

Table A-1 shows the interactive nature of the program's input routine. Table A-2 displays the listing of the input assumptions and acts both as a means for the user to verify the assumptions and for the formal record of the simulation run.

The output from the OCMHD simulation is shown in Table A-3, displaying the range of uncertainty associated with each of the 109 performance measures. Minus numbers, such as -1., or letters, such as NA, are indications that these are performance values that are not predicted by the particular modules chosen by the user.

Table A-4 presents the code for identifying specific pieces of information that the user may be interested in retrieving from the online documentation. Tables A-5 and A-6 show the retrievals of all OCMHD power plant information and LAMM health impact information. References are almost all available in this report's bibliography. The AEGIS program and bibliography will be available to the public late in 1978 upon completion of the NEES-NUSCO Project.

Table A-1 Input session for use of AEGIS program - terminal responses are in CAPITALS, user responses are in lower case; this is an example of the no-prompt option.

```
exec aegis
CHECK TERMINAL LINESIZE = 120 OR MORE
EXECUTION BEGINS...
    ALTERNATIVE ELECTRIC GENERATION IMPACT SIMULATOR
         AEGIS - VERSION  6
    DATA UPDATED  7/78

         AT ANY TIME USE NAMELIST VARIABLE=0 TO STOP OR RESTART RUN

    IS THIS AN ACTUAL RUN OR DEBUG RUN?  TYPE A OR D
a
    ALL OPTION VARIABLE DEFAULTS ARE 1
    NN=1 TO 10 FOR NUMBER OF EXAMPLES CARRIED, NN=1 ONLY FOR VERSION 2,
    NP=1 FOR PROB OR 2 FOR MEDIAN DISPLAYS,
    ND=1 FOR JUST FINAL DISPLAY OR =2 FOR DISPLAY ALONG THE WAY,
    NQ=1 FOR FULL PROMPTING DESCRIPTIONS OR 2 FOR MINIMUM PROMPTS, 3  FOR NO PROMPTS

&PRINT NN,NP,ND,NQ &END <AS INTEGERS>
&print nn=1,np=1,nd=1,nq=3 &end

Z1=SIZE,Z2=YEAR,Z3=FUEL,Z4=PREC,Z5=COMB,Z6=SORB,Z7=DCAP,Z8=PART
&ZLIST Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8 &END <AS INT>
&zlist z1=1900,z2=1998,z3=1,z4=1,z5=6,z6=1,z7=70,z8=1 &end

Z9=SCRUB,Z10=STACK,Z11=MET,Z12=SULF,Z13=SMOG,Z14=POP,Z15=SCAL,Z16=HEAL,Z17=RAD,Z18=INDEX
&ZLIST Z9,Z10,Z11,Z12,Z13,Z14,Z15,Z16,Z17,Z18 &END <AS INT, EXC Z15 DEC>
&zlist z9=1,z10=235,z11=1,z12=1,z13=1,z14=2,z15=.9,z16=3,z17=1,z18=1 &end
    AEGIS - VERSION M  GD 13   UPDATED  7/78
```

Table A-2 Display to user of the assumptions that will be used in this particular session.

```
 |-------------|
 | ASSUMPTIONS |
 |-------------|
   SIZE<MWE>                 1900.0
   YEAR COMPL                1998.0
   FUEL TYPE            NAT RANGE BITUMINS COALS
   PRECL TYPE           NONE
   GENERATYPE           COALFIRED OPEN CYCLE MHD
     DES CAPAC FAC<%>        70.000
     STORAGE CAP<MWH>        .0
     SORBENT TYPE       NONE
   ABATE TYPES:
     PART TYPE          NONE
     SCRUB TYPE         NONE
     STACK HT<M>             235.00
   MET SITE TYPE        STANDARD AMBIENT SCALING
   AEROCHEM MODELS:
     SULFATION TYPE     NONE
     SMOG TYPE          NONE
   DENSITY PATTERN      INDIAN POINT IN 1980 EST
     SCALED BY               .90000
   HEALTH/IMPACTS:
     CHEM HEALTH MOD    LINEAR ADD MORT MODEL
     RAD HEALTH MOD           NONE
     POLLUTION INDEX          NONE

FOR CHANGES NQ=4,OTHERWISE NQ=3
 &PRINT NQ &END
 &print nq=3 &end
```

Table A-3 Performance measures for the technology/site options chosen for this simulation.

```
!------------------------------!---------------------------------------------------------------------------!
! CUMULATIVE PROB MEASURES     !  MINIMUM       1 DEV LO       MEDIAN         1 DEV HI       MAXIMUM       !
! PROB VALUE < THIS VALUE      !  .0000         .1587          .5000          .8413          1.0000        !
!------------------------------!---------------------------------------------------------------------------!

!-------------------!
! ECONOMIC FACTORS !
!-------------------!
  INVEST COST<MIL $>                1219.8        1364.2         1529.5         2095.7         2736.0
  NORMALIZED INVEST<$1000/MWE>      642.00        718.00         805.00         1103.0         1440.0
  OPERATING COSTS:
    FIXED OPER COST<$/MWE/YR>       .11248E+06    .12579E+06     .14104E+06     .19325E+06     .25229E+06
    VARIABLE OPER COST<$/MWH>       7.4159        8.8692         11.229         14.377         19.852
      OP&MAIN<$/MWH>                1.6000        1.7000         2.8000         3.2000         4.0000
      FUEL<$/MWH>                   5.8159        7.1692         8.4289         11.177         15.852
  COST OF ELECT<MILS/KWH>           25.759        29.383         34.229         45.892         60.995
    CAP COST<MILS/KWH>              18.343        20.514         23.000         31.514         41.143
    OP COST<MILS/KWH>               1.6000        1.7000         2.8000         3.2000         4.0000
    FUEL COST<MILS/KWH>             5.8159        7.1692         8.4289         11.177         15.852
!----------------------!
! PERFORMANCE FACTORS !
!----------------------!
  OPER CAP FAC<%>                   55.000        63.000         68.000         70.000         75.000
  ENERGY EFF ONSITE<%>              39.819        43.347         46.147         48.068         49.867
!----------------!
! APPLICABILITY !
!----------------!
  COMMERC YR<2000MWE ONLINE>        1995.0        1996.0         1999.0         2003.0         2021.0
  INSTALLED CAP<MWE>                583.00        583.00         583.00         583.00         583.00
  LARGEST FACILITY<MWE>             500.00        500.00         500.00         500.00         500.00
!------------------------!
! RESOURCE REQUIREMENTS !
!------------------------!
  LAND USE ONSITE<ACRES>            70.490        96.900         370.50         659.30         1187.5
  LAND DISTURB FUEL<ACRES/YR>       63.776        99.243         120.60         146.74         179.70
  LAND DISPOSE WASTE<ACRES/YR>      59.850        86.450         119.70         151.62         196.84
  WATER CONSUMP<MIL GAL/YR>         2394.0        2926.0         4123.0         5985.0         7315.0
!---------------------------!
! ENVIRONMENTAL CONSEQUENCES !
!---------------------------!
  AIR EMIS ONSITE<GM/MIN>:
    SOX                             101.82        1287.7         42475.         .12990E+06     .48523E+06
      SULFATES                      8.1452        90.141         2973.3         9093.0         33819.
      SULF ACID AEROS               1.2727        12.877         504.40         1515.5         5661.0
    NOX                             5700.0        14250.         17100.         29450.         64600.
     NO                             5700.0        14250.         17100.         29450.         64600.
```

Table A-3 Continued display of performance measures.

```
03, OXID                          .64600E-03    .20900E-02    .64600E-02    .20330E-01    .64600E-01
PART TOTAL                        9690.0        47500.        77900.        98800.        .11590F+06
  PART RESPIR                     7030.0        32300.        55100.        68400.        81700.
CO                                15960.        53200.        .15960E+06    .53200E+06    .15960E+07
CO2                               .38000E+07    .47500E+07    .57000E+07    .76000E+07    .11400E+08
HC TOTAL                          3.0400        9.8800        30.400        98.800        304.00
   INERT HC                       2.4320        7.9800        24.320        79.800        243.20
   REACTIVE HC                    3.0400        .98800        3.0400        9.8800        30.400
   OXYG HC                        .30400E-01    .98800E-01    .30400        .98800        3.0400
   POLY ORG MAT                   .26600        .89300        2.6600        8.9300        27.360
TRACE ELEM:
   ARSEN                          .34397E-01    3.8291        23.482        150.89        398.10
   BERYL                          .13759E-01    .79669        5.1235        14.164        32.105
   CAD                            .68794E-02    .37236        6.9642        134.90        452.14
   CHROM                          .27518        8.5587        57.575        163.29        577.89
   COB                            .68794E-01    2.5087        32.058        104.33        368.13
   LEAD                           .27518        8.0305        58.253        372.98        933.18
   MANG                           .41276        12.199        206.85        695.06        1937.0
   MERC                           .13759E-02    .23272E-01    .83745E-01    .29607        1.7123
   NICK                           .20638        11.500        88.225        256.64        847.57
   SELEN                          .30957E-01    .45614        2.6128        7.3554        24.721
   TIN                            .68794E-01    2.2683        20.057        131.24        540.32
   VANAD                          .75673        19.251        95.875        244.22        584.31
   ZINC                           .41276        30.254        820.91        9270.6        41223.
  RADIOACT TO AIR<CUR/YR>         .31402E-03    .29245E-01    .11002        .23652        .58511
WATER EMIS ONSITE<TONS/YR>        .44245E+06    .52351E+06    .60302E+06    .71259E+06    .88853E+06
  INORGANIC<TONS/YR>              .39860E+06    .47140E+06    .54272E+06    .64197E+06    .79868E+06
  ORGANIC<TONS/YR>                43846.        52103.        60302.        70617.        88853.
  THERMAL<10*12 BTU/YR>           25.510        28.119        30.151        33.016        36.939
  RADIOACT TO WAT<CUR/YR>         .0            .0            .0            .0            .0
SOLID WASTES<TONS/YR>             .60753E+06    .26624E+07    .38457E+07    .53221E+07    .11083E+08
  RADIOACT SOLIDS<CUR/YR>         .0            .0            .0            .0            .0
ATMOS DILU FAC<UG/M3/G/MIN>
  GASEOUS:
    1 HOUR                        .83301E-06    .14072E-05    .33154E-05    .66555E-05    .11353E-04
    3 HOUR                        .15048E-05    .25421E-05    .59892E-05    .12023E-04    .20509E-04
    8 HOUR                        .19885E-05    .33592E-05    .79143E-05    .15887E-04    .27101E-04
    24 HOUR                       .25796E-05    .43578E-05    .10267E-04    .20611E-04    .35158E-04
    3 DAY                         .32783E-05    .55381E-05    .13048E-04    .26193E-04    .44680F-04
    1 MON                         .44069E-05    .74446E-05    .17540E-04    .35210E-04    .60062E-04
    ANNUAL                        .53742E-05    .90788E-05    .21390E-04    .42939E-04    .73246E-04
  PARTICULATES:
    1 HOUR                        .57056E-06    .74611E-06    .19311E-05    .34233E-05    .51789E-05
    3 HOUR                        .10307E-05    .13478E-05    .34885E-05    .61841E-05    .93554E-05
    8 HOUR                        .13620E-05    .17810E-05    .46098E-05    .81719E-05    .12363E-04
    24 HOUR                       .17669E-05    .23105E-05    .59802E-05    .10601E-04    .16038E-04
    3 DAY                         .22454E-05    .29363E-05    .75999E-05    .13473E-04    .20381E-04
    1 MON                         .30184E-05    .39472E-05    .10216E-04    .18111E-04    .27398E-04
    ANNUAL                        .36810E-05    .48136E-05    .12459E-04    .22086E-04    .33412E-04
```

Table A-3 Completion of display; -1.0 values indicate information not predicted by modules chosen.

```
OCCUP HEALTH:
  MORT ONSITE<PER YR>               .63776E-01     .82703E-01     .10768         .13757         .17970
  MORB ONSITE<PER YR>               .63776         .87665         1.8521         3.3016         4.4926
  DAYS LOST ONSITE</YR>             239.16         364.72         792.55         1283.9         1797.0
  MORT OFFSITE<PER YR>              .79720E-01     .41351         .86146         1.3757         2.1964
  MORB OFFSITE<PER YR>              2.1524         4.7140         54.617         87.583         100.83
  DAYS LOST OFFSITE</YR>            53.731         154.65         294.62         3466.7         9584.2
PUBLIC HEALTH<ROUTINE>:
  MORTALITIES<PER YR>               .94463E-01     1.0952         6.3197         18.926         56.097
    CANCER<TOTAL>                  -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CARDIOVAS                      -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    BRONCHOPULM                    -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CNS                            -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MUTATIONS<TOTAL>                 -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MORBIDITIES<PER YR>              -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    RESPIR                         -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      ASTHMA                       -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      PNEUM                        -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      CHRONIC                      -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      CHILDREN                     -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    THYROID                        -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CARDIOVAS                      -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MANDAYS LOST<PER YR>             -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
PUBLIC HEALTH<OFFSITE>:
  MORTALITIES<PER YR>              -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CANCER<TOTAL>                  -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MUTATIONS<TOTAL>                 -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MORBIDITIES<PER YR>              -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MANDAYS LOST<PER YR>             -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
PUBLIC HEALTH<CATAST>:
  PROB OF OCCUR<PER YR>             .79720E-07     .39697E-06     .68917E-06     .11739E-05     .15974E-05
  MORTALITIES<PER YR>               .63776         1.2405         1.5506         1.9259         2.7954
    CANCER<TOTAL>                   .39860E-05     .25638E-04     .56857E-04     .35767E-03     .86856E-03
    BRONCHOPULM                     .11958E-04     .49622E-04     .21537E-03     .50441E-03     .11980E-02
    CARDIOVAS                       .79720E-04     .37216E-03     .86146E-03     .20176E-02     .89851E-02
  MUTATIONS<TOTAL>                 -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MORBIDITIES<PER YR>               6.3776         17.368         24.121         32.099         40.932
    THYROID                        -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MANDAYS LOST<PER YR>              637.76         1736.8         2412.1         3209.9         4093.2
INDEXES AND COSTS:
  PUBLIC HEALTH COSTS<$/YR>        -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  BIOTA COSTS<$/YR>                -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MAT DAMAGE COSTS<$/YR>           -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  AESTH COSTS<$/YR>                -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  SUBJECTIVE INDEXES               -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
FOR ANOTHER RUN TYPE: DO   OR:  NOT
not
END
```

Table A-4 Code and format for on-line documentation retrieval.

```
  AEGIS DOCUMENTATION IDENTIFICATION CODE

AEGIS - ALTERNATIVE ELECTRIC GENERATION IMPACT SIMULATOR, VERSION M005D012
FOR FURTHER INFORMATION CONTACT: J. GRUHL, E38-408, 77 MASS. AVE., CAMBRIDGE MA
                          (617)253-8025 OR MESSAGE AT -3404
D = DOCUMENTATION TEXT IDENTIFIER
|NN = MODULE NUMBER    01=FUELS
|||                    02=PRETREATMENT
|||                    03=COMBUSTION
|||                    04=ADDITIVE
|||                    05=PARTICULATE ABATEMENT
|||                    06=OTHER ABATEMENT
|||                    07=ATMOSPHERIC CHARACTERISTICS AND DISPERSION MODEL
|||                    08=AEROCHEMICAL MODEL
|||                    09=DEMOGRAPHIC CHARACTERISTICS
|||                    10=CHEMICAL HEALTH IMPACTS
|||                    11=RADIATION HEALTH IMPACTS
|||                    12=OTHER IMPACT MEASURES
|||NN = SPECIFIC MODEL (WITHIN MODULE)
|||||NN = DESCRIPTIVE INFORMATION (FOR SPECIFIC MODEL)
|||||||NN = LINE NUMBERS (FOR SAME DESCRIPTIVE INFORMATION)
|||||||||         LINES  01=CONCENSUS PROBABILISTIC BREAKDOWN, FIVE NUMBERS
|||||||||                       MINIMUM, .00 CUMULATIVE PROBABILITY
|||||||||                       ONE DEV LOW, .16 CUMULATIVE PROBABILITY
|||||||||                       MEDIAN, .50 CUMULATIVE PROBABILITY
|||||||||                       ONE DEV HIGH, .84 CUMULATIVE PROBABILITY
|||||||||                       MAXIMUM, 1.00 CUMULATIVE PROBABILITY
|||||||||              02 TO 09=CORRELATED CONDITIONALS
|||||||||              10 TO 99=SPECIFIC SOURCES AND NUMBERS
D11223344
   IS EXAMPLE DOCUMENTATION LINE IDENTIFIER FOR INFORMATION ABOUT MODULE 11,
        MODEL 22, ROW OF DESCRIPTIVE INFORMATION 33, LINE 44
```

Table A-5 On-line retrieval of Open Cycle Coal-Fired MHD data.

```
D03060000     VERSION D013
D03060001 DESCRIPTION  OPEN CYCLE COAL-FIRED MHD
D03060002  DIRECT AIR PREHEATING AT 1350K, 95% STOICHIOMETRIC AIR, 2 STAGE
D03060003  COMBUSTOR, DIRECT COAL-FIRED, 80% SLAG REJECTION, 1.0% K2CO3 SEEDING,
D03060004  .75 MACH FLOW RATE, 6 ATM, 6 TESLA MAGNETIC FIELD, STEAM BOTTOMING
D03060005  CYCLE OF 24.1MW/M2/811K/811K
D03060101 OVERALL ENERGY EFF%          45.6    47.0    48.3    48.7    49.2
D03060102  +(1.-SULFUR% OF COAL TIMES 0.9)
D03060103  +0 FOR ILL6, -.35 MONT ROSEBUD, -2.0 N.D., -6.05 SRC (GRUHL,NOV1977)
D03060104  TIMES 1. FOR 2%MOISTURE, .97 FOR 10%, .86 FOR 27.4% (CUTTING,1977)
D03060110   (WITVER,1976) 46-55
D03060111   (GRUHL,NOV1977) 45.6-49.2
D03060112   (POMEROY,ET AL,1978) 48.3-49.2
D03060113   (HALS,JACKSON,1969) 50-60
D03060114   (FELDMANN,SIMONS,BIENSTOCK,1970) THERMAL 50.8-51.9
D03060115   (BERGMAN,BIENSTOCK,1976) 45.6-50.14
D03060116   (JACKSON,ET AL,1976) 47
D03060117   (CUTTING,ET AL,1977) 46-46.9
D03060118   (SEIKEL,HARRIS,1976) 41-53,42-50(W.E.CO.),48.3(G.E.CO.)
D03060119   (POWELL,ULMER,1974) 50-55
D03060120   (PENNY,BOURGEOIS,CAIN,1977) 55-60
D03060121   (GENERAL ELECTRIC,1976) 44-55
D03060122   (GENERAL ELECTRIC,1976)SRC 40-46
D03060123   (NASA,1977) 48.3-48.7
D03060124   (PEPPER,YU,1975) 52 THERMAL
D03060125   (WESTINGHOUSE,1976)DIRECT AIR PREHEAT 44-49,44-54
D03060126   (NASA,1976) LOW BTU PREHEAT 46-54
D03060201 CAP INVEST 1978$/KWE         642.    718.    805.    1103.   1440.
D03060210   (WITWER,1976) BASELOAD 1975$ 600
D03060211   (POMEROY,ET AL,1978) 805
D03060212   (HALS,JACKSON,1969) 90-120
D03060213   (ROSA,ET AL,1970) 35-55 PEAKING
D03060214   (SEIKEL,HARRIS,1976) 718
D03060215   (GENERAL ELECTRIC,1976) 910-1440
D03060216   (NASA,1977) 1103 (W.E.CO.)
D03060217   (PEPPER,YU,1975) 340-440
```

Table A-5 (continued)

```
D03060218   (NASA,1977) 642 (G.E.CO.)
D03060301 C O E 1978MILS/KWH           27.1    36.0    42.0    48.5    55.5
D03060302  THIS HAS A TIGHTER DISTRIBUTION THAN THE SUM OF ITS COMPONENT
D03060303  PROBABILITIES DUE TO INVESTMENT/OPERATING COST TRADEOFFS
D03060310   (WITWER,1976) 1977$ WITH 1$/MBTU COAL  28
D03060311   (LEVI,1978) 32
D03060312   (NASA,1975) 41-48(G.E.CO.),27-35(W.E.CO.),34-42(LOW BTU)
D03060313   (POMEROY,ET AL,1978) 34-43 BASELOAD
D03060314   (POMEROY,ET AL,1978) 130 PEAKING
D03060315   (HALS,JACKSON,1969) 3.34-4.26
D03060316   (SEIKEL,HARRIS,1976) 42-49(G.E.CO.),32-50(W.E.CO),31.8(G.E.CO.)
D03060317   (GENERAL ELECTRIC,1975) 41.5-55.5
D03060318   (NASA,1977) 27.1-43.9
D03060401 C O E CAP 1978MILS/KWH      14.0    22.7    25.5    34.8    37.7
D03060402  COE CAP= CAPITAL INV TOTAL X CAPITAL COST FACTOR /(LOAD FACTOR X CAP)
D03060403  CAP COST FACT = ABOUT 10% PUBLIC, 20% PRIVATE SECTOR
D03060404  20% IS USED IN SIMULATOR, THESE VALUES ARE FOR COMPARISON PURPOSES
D03060405  ONLY WITH THESE VALUES DETERMINED ENDOGENOUSLY
D03060410   (WITWER,1976) CCF 10% 10.6,CCF 20% 21.2
D03060411   (GENERAL ELECTRIC,1976) 22.7,22.7,24.4,25.5,29.5,18.4
D03060412   (CORMAN,ET AL,1976)34.9,33.2,37.7,34.8,35.7,35,35,44.7,32.0
D03060413   (NASA,1977) 22.7
D03060414   (HALS,JACKSON,1969) 2.57-1.93
D03060415   (POMEROY,ET AL,1978)CAP FAC .7=14,.4=24.5,.15=65.3
D03060501 C O E O&M 1978MILS/KWH      1.6     1.7     2.8     3.2     4.0
D03060510   (WITWER,1976) 1.0
D03060511   (GENERAL ELECTRIC,1976) 1.7,1.7,1.7,1.7,1.8,1.7
D03060512   (CORMAN,ET AL,1976)2.8,2.9,3.2,2.9,2.9,2.8,2.8,3.6,2.3
D03060513   (HALS,JACKSON,1969) .27-.33
D03060514   (NASA,1977) 1.7
D03060515   (POMEROY,ET AL,1978)CAP FAC=.7=3.2, .4=3.6, .15=4.8
D03060601 C O E FUEL MILS/KWH          6.1     6.3     7.3     8.8    11.0
D03060602  COE FUEL = $/MBTU COAL X .003412MBTU/KWH / .01EFFICIENCY%
D03060603  DETERMINED ENDOGENOUSLY, THESE VALUES FOR COMPARISON ONLY
D03060610   (WITWER,1976) 6.2 FOR 6200BTU/KWH, $1.00/MBTU COAL
D03060611   (NASA,1977) 7.3
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Table A-5 (continued)

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D03060612   (HALS,JACKSON,1969) .20/MBTU COAL = 1.36
D03060613   (POMEROY,ET AL,1978) 16.5
D03060614   (GENERAL ELECTRIC,1976) 7.3,7.3,7.3,7.3,7.3,11.0
D03060615   (CORMAN,ET AL,1976)6.2,6.3,6.3,6.1,6.3,6.3,6.3,6.6,8.8
D03060616   (CORMAN,ET AL,1976) CHANGE 20% FUEL = 1.3 CHANGE
D03060701 MAX AVAILAB %                55.     63.     68.     70.     75.
D03060702  SHOULD BE DECREASING FN OF SIZE OF MODULES BUT NO DATA
D03060710   (JACKSON ET AL,1976) 70
D03060711   (JACKSON,ET AL,1976) 20% TOTAL UNAVAILABILITY
D03060712   (POMEROY,ET AL,1978) 65 = 100-20FORCED-15PLANNED
D03060801 COMMERC YR                 1995    1996    1999    2003    2021
D03060802  FOR COAL-FIRED FACILITIES, NOT GAS OR OIL WHICH ARE MUCH SOONER
D03060810   (WITWER,1976) 1995
D03060811   (PEPPER,YU,1975) 1988
D03060812   (POMEROY,ET AL,1978) 2003
D03060813   (SEIKEL,HARRIS,1976) 1996-1999
D03060814   (PENNY,BOURGEOIS,CAIN,1977) 2000
D03060815   (CORMAN,ET AL,1976) 1997
D03060901 INSTALLED CAP MWE          83.     583.    583.    2600.   2600.
D03060902  AT YEARS 1985 1990 1995 2000 2005
D03060910   (GRUHL,NOV1977) .2 1978,4.3 1979,13 1981, 83 1985, 583 1989
D03061001 LARGEST FAC MWE            70.     500.    500.    2000.   2000.
D03061002  AT YEARS 1985 1990 1995 2000 2005
D03061010   (GRUHL,NOV1977)  .2 1978,4 1979,9 1981, 70 1985, 500 1989
D03061101 LAND ONSITE ACRES/MW       .0371   .051    .195    .347    .625
D03061110   (GENERAL ELECTRIC,1976) MAIN PLANT 3.71 PER 100MWE
D03061111   (HARRIS,SHAH,1976) 5.1 PER 100MWE
D03061112   (HOOVER,ET AL,1976) 11.64 TO 24.38 PER 100MWE
D03061113   (HOOVER,ET AL,1976) PLUS RAILROAD ACCESS 23.05 TO 28.13 PER 100MWE
D03061201 LAND USE WASTE ACRES/MWY   .045    .065    .090    .114    .148
D03061210   (HARRIS,SHAH,1976) 84/1932MW
D03061211   (HOOVER,ET AL,1976) 11.36 TO 14.75/100MW
D03061301 WATER CONS MIL GAL/MWY     1.8     2.2     3.1     4.5     5.5
D03061310   (JACKSON,ET AL,1977) 24MWE 163GAL/MIN
D03061311   (GENERAL ELECTRIC,1976) .22 GAL/KWH
D03061312   (SHAW,CAIN,1977) .727KG/KWH
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Table A-5 (continued)

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D03061313   (HARRIS,SHAH,1976) .33GAL/KWH
D03061314   (HOOVER,ET AL,1976) .53 TO .612 GAL/KWH
D03061401 OUTLET VEL M3/MIN/MW        17.25    17.25    17.25    17.25    17.25
D03061402  THIS NUMBER NOT USED IN CURRENT VERSION OF PROGRAM
D03061403  HAS NOT BEEN COMPUTED, 17.25 IS CONV COAL NUMBER
D03061410   (GENERAL ELECTRIC,1976) 10.97 MIL LB/HR 14.7PSIA, 1932MW
D03061411   (WESTINGHOUSE,1976) 3435.8 LB/S, 14.7PSIA, 1900MW
D03061501 SOX % REL                   0.4      1.0      16.      30.      66.
D03061510   (ARGYROPOLIS,1976) 0.4
D03061511   (GENERAL ELECTRIC,1976) ASSUMING 3%S COAL 66.
D03061512   (HARRIS,SHAH,1976) ASSUMING 3%S COAL 18.
D03061512   (RESEARCH AND EDUC ASSOC,1976) ASSUMING 3%S COAL 16.
D03061601 SULFATES % REL              0.032    0.07     1.12     2.10     4.60
D03061602  ASSUMPTION ON K2SO4 COLLECT EFF AND SO2/SO3 RATIO THIS IS
D03061603  ABOUT .07 OF THE SOX RELEASE NUMBER
D03061701 SULF ACID % REL             0.005    0.010    0.190    0.350    0.770
D03061702  ABOUT 1/6 OF SULFATES, NO DATA
D03061801 NOX G/MIN/MW                3.0      7.5      9.0      15.5     34.0
D03061802  CONVERSION IS LB/MBTU INPUT = ABOUT 830PPM = .0067LB/KWH
D03061803  OR APPROXIMATELY 50.2 G/MIN/MW
D03061810   (GENERAL ELECTRIC,1976) 0.3 LB/MBTU
D03061811   (SHAW,1978) 0.71 LB/MBTU
D03061812   (FOLSOM,1978) OLD 0.72, NEW .685 LB/MBTU
D03061813   (MORI,TAIRA,1972) 243PPM
D03061814   (MORI,TAIRA,1973) 50PPM
D03061815   (PEPPER,EUSTIS,KRUGER,1972) 283PPM
D03061816   (PENNY,BOURGEOIS,CAIN,1977) 135 TO 300PPM
D03061817   (BIENSTOCK,ET AL,1973) 150PPM
D03061818   (HALS,LEWIS,1972) 160-260PPM
D03061819   (REA,1976) 155PPM
D03061901 NO G/MIN/MW                 3.0      7.5      9.0      15.5     34.0
D03061902  ESSENTIALLY THE SAME AS NOX, UNSTABLE AND GOES TO ZERO
D03062001 OXID MG/MIN/MW              .00034   .0011    .0034    .0107    .0340
D03062002  SET AT ABOUT .0001PPM, ESSENTIALLY ZERO IN FINE-TUNED DEVICE
D03062101 PART TOT G/MIN/MW           5.1      25.      41.      52.      61.
D03062102  PRECIPITATION MUST BE 99.5% OR BETTER TO BE
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Table A-5 (continued)

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D03062103  ECONOMIC IN RECOVERING VALUABLE SEED FOR RECYCLE
D03062104  SRC FUEL YIELDS 1/17TH PARTICULATES OF OTHERS
D03062105  LB/MBTU = .075LB/KWH = ABOUT 570G/MIN/MW
D03062110   (GENERAL ELECTRIC,1976) .1LB/MBTU INPUT, .008LB/KWH
D03062111   (HARRIS,SHAH,1976) .1LB/MBTU INPUT, .007LB/KWH OUTPUT
D03062112   (SHAW,CAIN,1977) 0.15G/KWHT, 0.32G/KWHE
D03062113   (GENERAL ELECTRIC,1976) SRC .06LB/MBTU,.00046LB/KWH
D03062201 PART RESP G/MIN/MW         3.7      17.0     29.0     36.0     43.0
D03062202  PRESUME ABOUT 70% PARTICULATES RESP AFTER SECOND CYCLONE
D03062301 CO G/MIN/MW                8.4      28.0     84.0     280.     840.
D03062310   (SHAW,CAIN,1977) NIL
D03062311   (BIENSTOCK,ET AL.,1971) 0
D03062312   (GENERAL ELECTRIC,1976) 0
D03062313   (HALS,LEWIS,1972) WITH SECONDARY STAGE 0.4 TO 0.6%
D03062314   (GRUHL,NOV1977) TUNED TO YIELD JUST A TRACE
D03062401 CO2 G/MIN/MW               2000.    2500.    3000.    4000.    6000.
D03062402  FLUID BEDS YIELD ABOUT 15% =? 3000G/MIN/MW?
D03062501 TOTAL HC G/MIN/MW          .0016    .0052    .016     .052     .160
D03062502  1.6 FROM FLUID BEDS
D03062510   (GENERAL ELECTRIC,1976) 0
D03062511   (ROSA,ET AL.,1970) 0
D03062601 INERT HC MG/MIN/MW         1.28     4.20     12.8     42.0     128.0
D03062602  PRESUME ABOUT 80% OF HC
D03062701 REACT HC MG/MIN/MW         .16      .52      1.60     5.20     16.00
D03062702  PRESUME ABOUT 10% OF HC
D03062801 OXYG HC MG/MIN/MW          .016     .052     .160     .520     1.600
D03062802  PRESUME ABOUT 1% OF HC
D03062901 POM MG/MIN/MW              .14      .47      1.40     4.70     14.40
D03062902  PRESUME ABOUT 9% OF HC
D03063001 ARSEN % REL                1.0      8.0      20.      33.      40.
D03063010   (GRUHL,NOV1977) 1-40
D03063101 BERYL % REL                1.0      13.0     38.0     63.0     75.0
D03063110   (GRUHL,NOV1977) 1-75
D03063201 CAD % REL                  1.0      12.0     33.0     54.0     65.0
D03063210   (GRUHL,NOV1977) 1-65
D03063301 CHROM % REL                1.0      17.0     50.0     84.0     100.
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Table A-5 (continued)

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D03063310   (GRUHL,NOV1977) 1-100
D03063401 COB % REL                1.0     14.0     40.0     67.0     80.0
D03063410   (GRUHL,NOV1977) 1-80
D03063501 LEAD % REL               1.0      8.0     20.0     33.0     40.0
D03063510   (GRUHL,NOV1977) 1-40
D03063601 MANG % REL               1.0     17.0     50.0     84.0    100.0
D03063610   (GRUHL,NOV1977) 1-100
D03063701 MERC % REL               1.0      3.0      5.0      8.0     10.0
D03063710   (GRUHL,NOV1977) 1-10
D03063801 NICK % REL               1.0     17.0     50.0     83.0     99.0
D03063802  TOP VALUE SHOULD REFLECT GOOD NUMBER FROM CONVENTIONAL COAL PLANT
D03063810   (HARRIS,SHAH,1976) 1
D03063901 SELEN % REL              1.0      6.0     15.0     25.0     30.0
D03063910   (GRUHL,NOV1977) 1-30
D03064001 TIN % REL                1.0     17.0     50.0     83.0     99.0
D03064002  TOP VALUE SHOULD REFLECT GOOD NUMBER FROM CONVENTIONAL COAL PLANT
D03064010   (HARRIS,SHAH,1976) 1
D03064101 VANAD % REL              1.0     12.0     35.0     59.0     70.0
D03064110   (GRUHL,NOV1977) 1-70
D03064201 ZINC % REL               1.0     13.0     36.0     60.0     72.0
D03064210   (GRUHL,NOV1977) 1-72
D03064301 RAD226 % REL             1.0     17.0     50.0     84.0    100.0
D03064310   (GRUHL,NOV1977) 1-100
D03064401 RAD228 % REL             1.0     17.0     50.0     84.0    100.0
D03064410   (GRUHL,NOV1977) 1-100
D03064501 WAT EM TOT TONS/10*12BTU IN5500.   6300.    7000.    7700.    8900.
D03064502  LB/KWHE = ABOUT 70600 TONS/10*12BTU IN
D03064510   (SHAW,CAIN,1977) 24.6 G/KWHT, 51.G/KWHE
D03064511   (HARRIS,SHAH,1976) .75LB/KWH
D03064512   (GENERAL ELECTRIC,1976) .09LB/KWH
D03064601 WAT EM INORG T/10*12BTU IN 5000.   5700.    6300.    7000.    8000.
D03064602  ASSUMING APPROXIMATELY 90% OF TOTAL WASTE IS INORGANIC
D03064701 WAT EM ORG T/10*12BTU IN   550.    630.     700.     770.     890.
D03064702  ASSUMING APPROXIMATELY 10% OF TOTAL WASTE IS ORGANIC
D03064801 WAT EM THERM % OF BTU IN   32.     34.      35.      36.      37.
D03064802  EARLIER DATA SET VERSION WAS BTU THERMAL/10*12BTU IN
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Table A-5 (continued)

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D03064810   (GENERAL ELECTRIC,1976) 2468BTU/KWH, SRC 2040BTU/KWH
D03064811   (HARRIS,SHAH,1976) 2377BTU/KWH
D03064901 RAD TO WAT CUR/10*12BTU IN 0.0      0.0      0.0      0.0      0.0
D03065001 SOL WASTES T/10*12BTU IN    4500.    5100.    5600.    6200.    7100.
D03065002  LB/KWHE = ABOUT 70600TONS/10*12BTU IN
D03065003  ASSUMING 48.3% EFFICIENCY, SOLID WASTES SHOULD BE
D03065004  COMPUTED AS 99.5% OF ASH OF INCOMING COAL
D03065010   (SHAW,CAIN,1977) 14.01G/KWHT, 29.G/KWHE
D03065011   (GENERAL ELECTRIC,1976) 0.082LB/KWH
D03065101 OTHER SOL WASTES T/10*12    0.0      0.0      0.0      0.0      0.0
D03065102  SULFUR IS RECOVERED THAT ENTERS SYSTEM AND DOES NOT EXHAUST BUT
D03065103  THIS IS CONSIDERED (MARGINALLY) SALEABLE PRODUCT, NO SEED LOSS
D03065201 RAD SOL CUR/10*12BTU IN     0.0      0.0      0.0      0.0      0.0
D03065301 OCC HEALTH MORT/10*12BTU IN.00080   .00100   .00125   .00150   .00180
D03065302  IN ABSENSE OF DATA SAME AS COAL PLANT, ALTHOUGH PRESSURIZED
D03065303  VESSEL SHOULD INCREASE THESE NUMBERS
D03065401 OCC HEALTH MORB/10*12BTU IN.008     .0106    .0215    .0360    .0450
D03065402  AGAIN SAME AS COAL PLANT IN ABSENSE OF DATA
D03065501 OCC HEALTH WDL/10*12BTU IN 3.0      4.41     9.20     14.0     18.0
D03065502  WORK DAYS LOST ALSO PRESUMED SAME AS CONVENT COAL IN ABSENSE OF DATA
D03065601 PUB H CATAST PROB/10*12     .10E-08 .48E-08 .80E-08 1.28E-08 1.6E-08
D03065602  REFLECTS THE PROBABILITY OF EXPLOSION OR COALPILE FIRE
D03065603  ASSUMES COAL FIRE 1/100 TO 1/1000 PROBABILITY OF OIL FIRE
D03065604  1000MWYR=29.89X10*12BTU IN X .01CAPFAC%/.01EFFIC%
D03065610   (BECKMAN,1976) 10-4 FOR OIL-FIRED PLANT WHERE > 10 MORTALITIES
D03065701 PUB H CATAST MORT/10*12     .008     .015     .018     .021     .028
D03065702  FOR CONVENT 36%EFF 100%CAPFAC COAL PLANT 12.0MWY=ABOUT 10*12BTU IN
D03065703  SHOULD INCLUDE MORTALITIES RESULTING FROM COALPILE FIRE PLUME
D03065704  AS WELL AS PUBLIC MORTALITIES FROM PRESSURIZED VESSEL EXPLOSION
D03065705  AND PUBLIC MORTALITIES FROM COAL TRANSPORT
D03065710   (CEQ,1973) 2.30/750MWY AT RR CROSSINGS
D03065711   (SAGAN,1974) 1.3/1000MWPLANT/YR
D03065712   (AEC,1974,WASH-1224) 0.55/1000MWPLANT/YR
D03065713   (GRUHL,SEP1976) 1.8X10*2 OIL-FIRE MORT / PLANT / FIRE / 10*7 POP
D03065801 PUB H CATAST CANC/10*12     .05E-06 .31E-06 .66E-06 3.9E-06 8.7E-06
D03065802  SHOULD BE CANCINOGENIC IMPACTS OF COALPILE FIRE PLUME
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Table A-5 (continued)

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D03065803  ASSUMING BETWEEN 1 AND 10 MILLION PERSONS EXPOSED TO PLUME
D03065810   (HICKEY,ET AL,1970) 54.6 ADDIT CANCERS PER MILLION FROM SO4.
D03065901 PUB H CATAST BRPU/10*12     1.5E-07 0.6E-06 2.5E-06 5.5E-06 12.E-06
D03065902  SHOULD BE BRONCHOPULM CASES FROM COALPILE FIRE PLUME
D03065903  ASSUME ABOUT SAME AS ANNUAL CASES
D03065910   (NAS,1975) .9-3.6X10*4 FOR 1000MWE REGULAR OPERATION
D03066001 PUB H CATAST CRVS/10*12     .1E-05  .45E-05 1.0E-05 2.2E-05 9.E-05
D03066002  SHOULD BE CARDIOVASCULAR CASES FROM COALPILE FIRE PLUME
D03066003  ASSUME ABOUT SAME AS ANNUAL CASES FROM NORMAL OPERATION
D03066010   (NAS,1975) .7-2.8X10*5 FOR 1000MWE NORMAL OPERATION
D03066101 PUB H CATAST MORB/10*12 IN .08      .21      .28      .35      .41
D03066102  SHOULD INCLUDE COALPILE FIRE CASES
D03066110   (CEQ,1973) 23.4/750MWY AT RR CROSSINGS
D03066201 PUB H CATAST WDL/10*12 IN  8.0      21.      28.      35.      41.
D03066202  SHOULD INCLUDE COALPILE FIRE CASES
D03066210   (CEQ,1973) 2340./750MWY AT RR CROSSINGS
D03066301 AIR EM THERM % OF BTU IN   7.2      8.0      8.9      9.8      10.5
D03066302  NOT DISPLAYED AS EMISSION, JUST USED FOR PLUME RISE COMPUTATIONS
D03066310   (GENERAL ELECTRIC,1976) 606BTU/KWH
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Table A-6 On-line retrieval of documentation of LAMM health impact model.

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D10030000     VERSION D013
D10030001 DESCRIPTION  LINEAR ADDITIVE MORTALITY MODEL - LAMM
D10030002  CRUDE, LINEAR MODEL BASED UPON CONCENSUS STANDARDS, IT ONLY
D10030003  PREDICTS ANNUAL INCREASES IN MORTALITY RATES, SOURCE IS
D10030004  (GRUHL,ET AL,NOV1976,P106), ACCURACY DEPENDS ON AMONG OTHER THINGS
D10030005  SMALLNESS OF REGIONS CONSIDERED
D10030010   TOTAL ADDITIONAL ANNUAL MORTALITIES PER 10*6 PERSONS IN SOME
D10030011   REGION NEAR POINT SOURCE = SUMMATION (REGIONAL MAXIMUM UG/M3 24HR
D10030012   AVERAGE CONCENTRATIONS OF NOX/455 + SOX/365 + CO/710000 + PART/260
D10030013   + ARSEN/.15 + BERYL/.01 + MERC/.10 + NICK/.03 +
D10030014   + RADIUMS(CURIES/YR)/.02 )
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